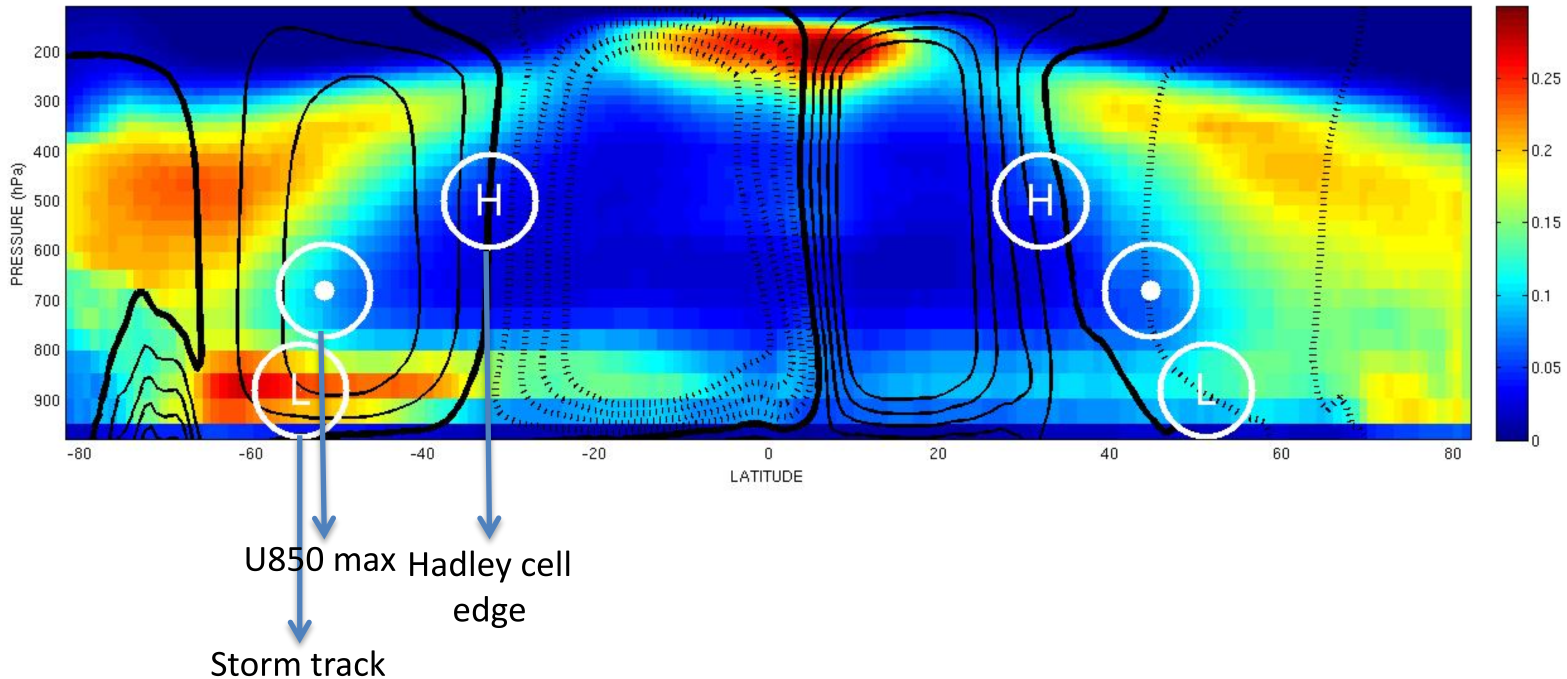
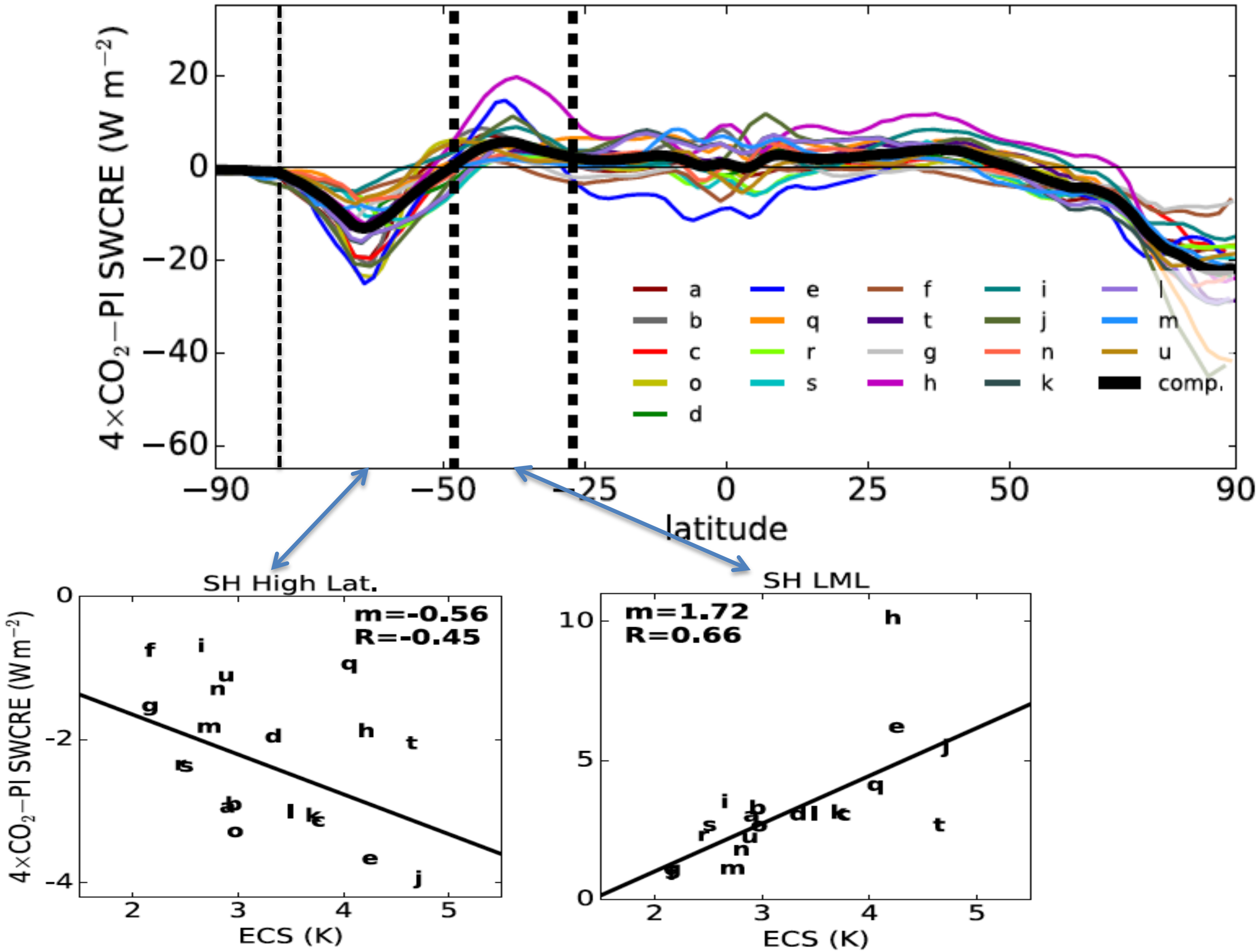
# Hadley cell expansion, Southern Ocean cloud radiative effect variability, and climate sensitivity in CMIP6 models

George Tselioudis, Bernard Lipat, Lorenzo Polvani, Kevin Grise, Aiko Voight, Derek Tropf

- How shifts in the main features of the atmospheric zonal mean circulation affect the components of the cloud radiative effect?
- How well do models simulate this cloud/circulation coupling and what are the effects of model simulation deficiencies on climate sensitivity?



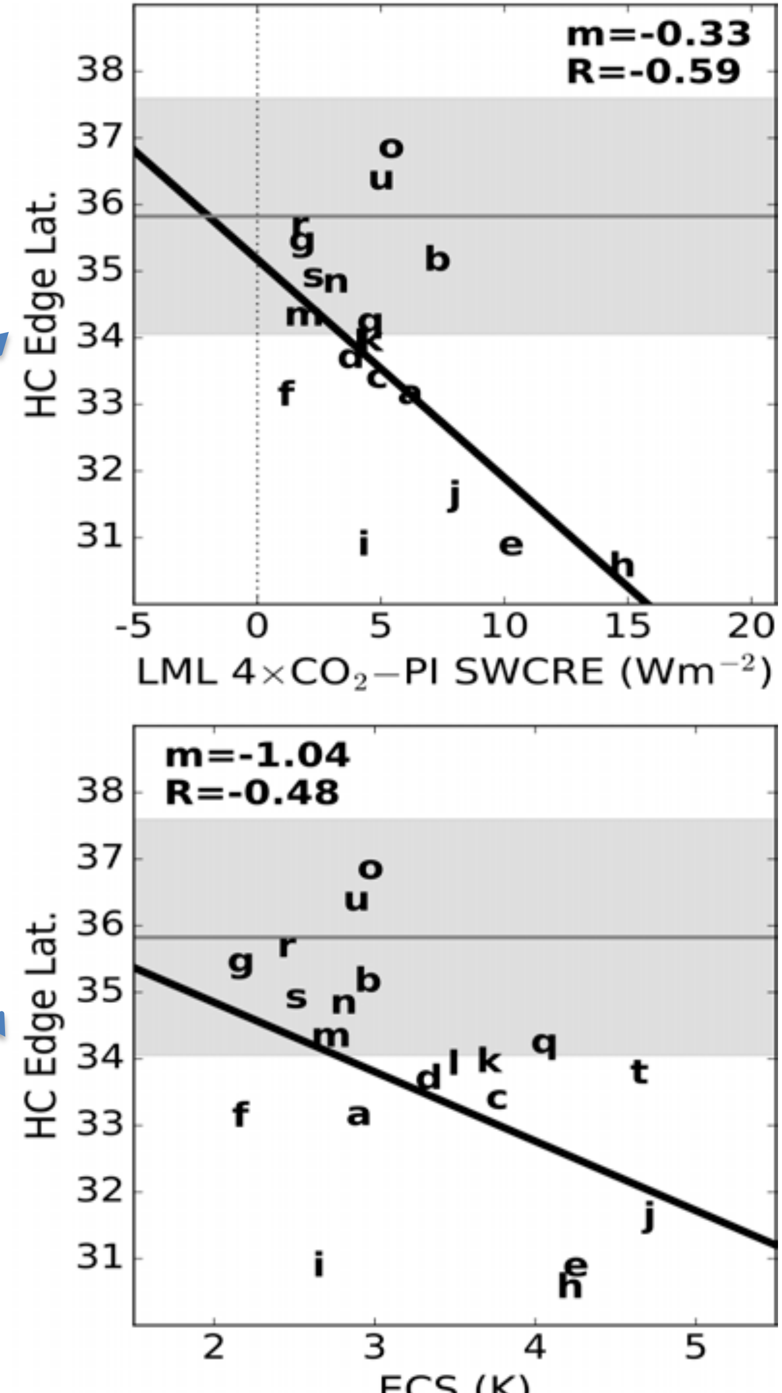
Annual 4xCO2 SWCRE changes in CMIP5 models and their relation to climate sensitivity




Lipat, Tselioudis, Grise, Polvani, GRL, 2017

In 4xCO2 runs:
LML SWCRE warming is significantly predicted by climatological HC edge position

Therefore, ECS is significantly constrained by the climatological HC edge position, and models with more realistic HC edge positions tend to have lower ECS values



B
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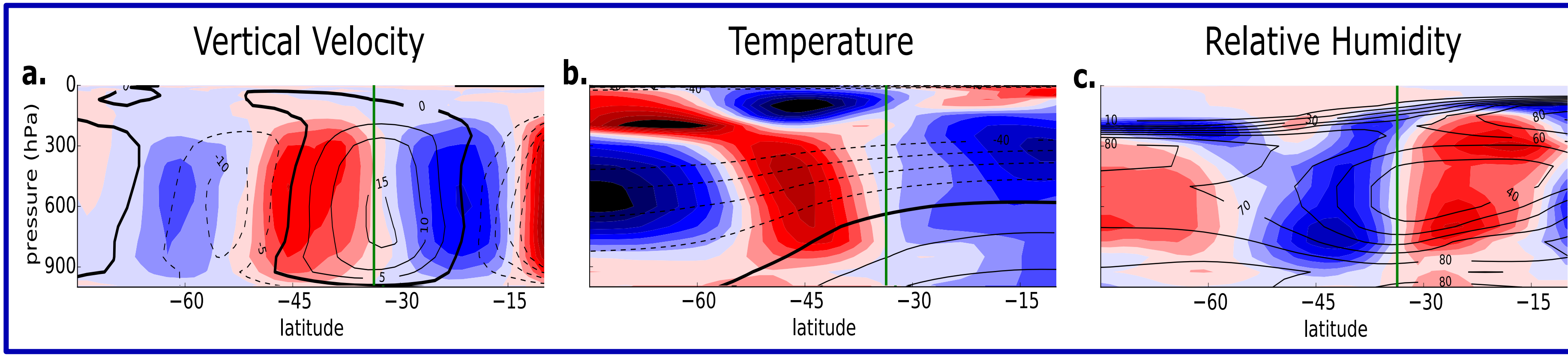
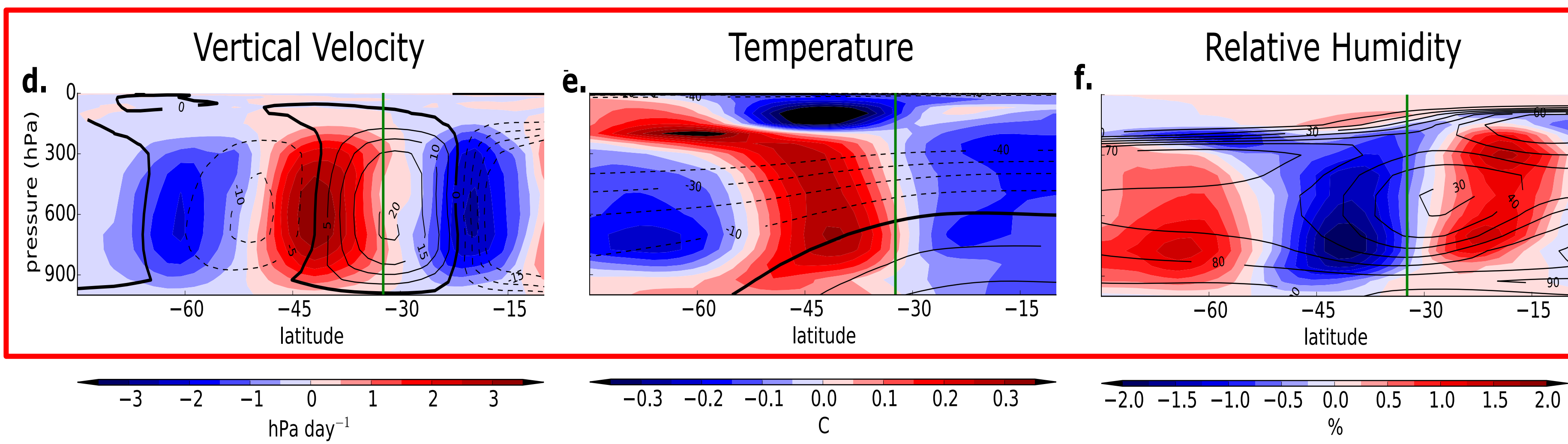
# ECHAM6

## Widest HC

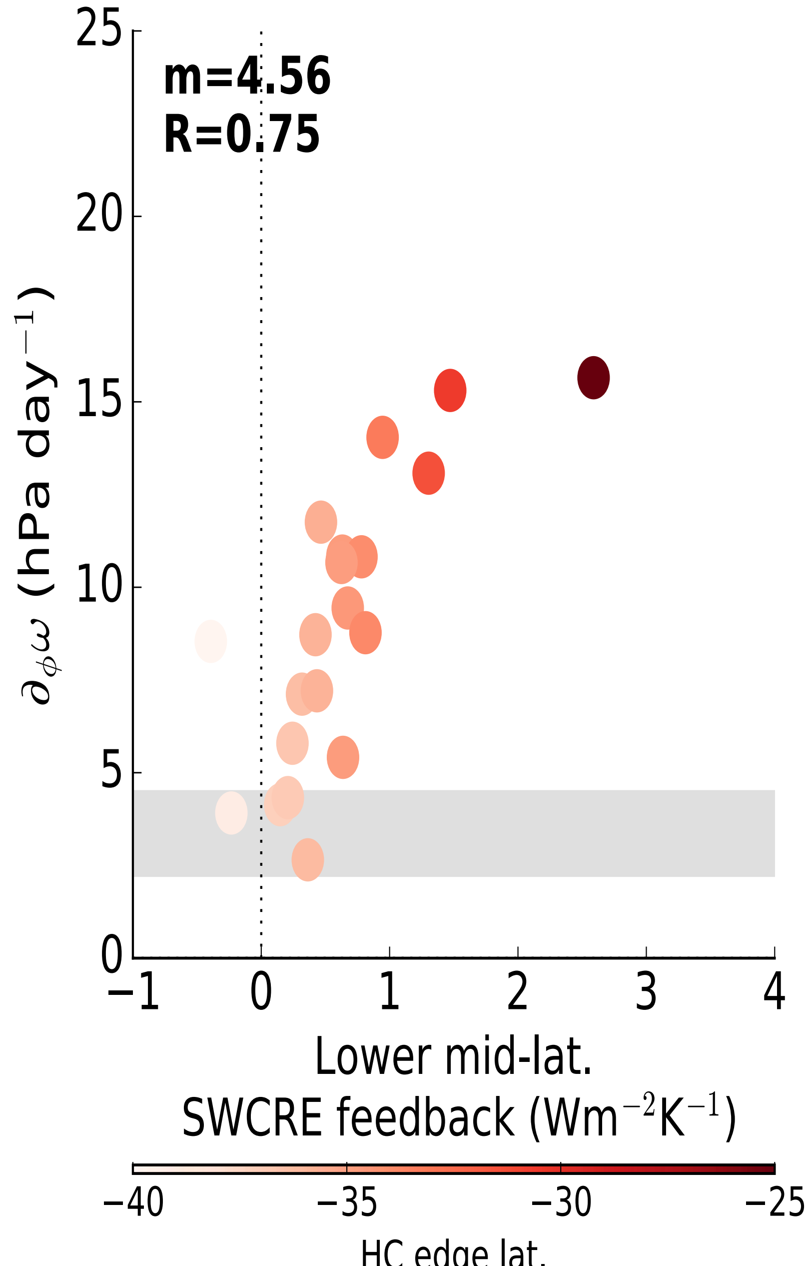



## Narrowest HC



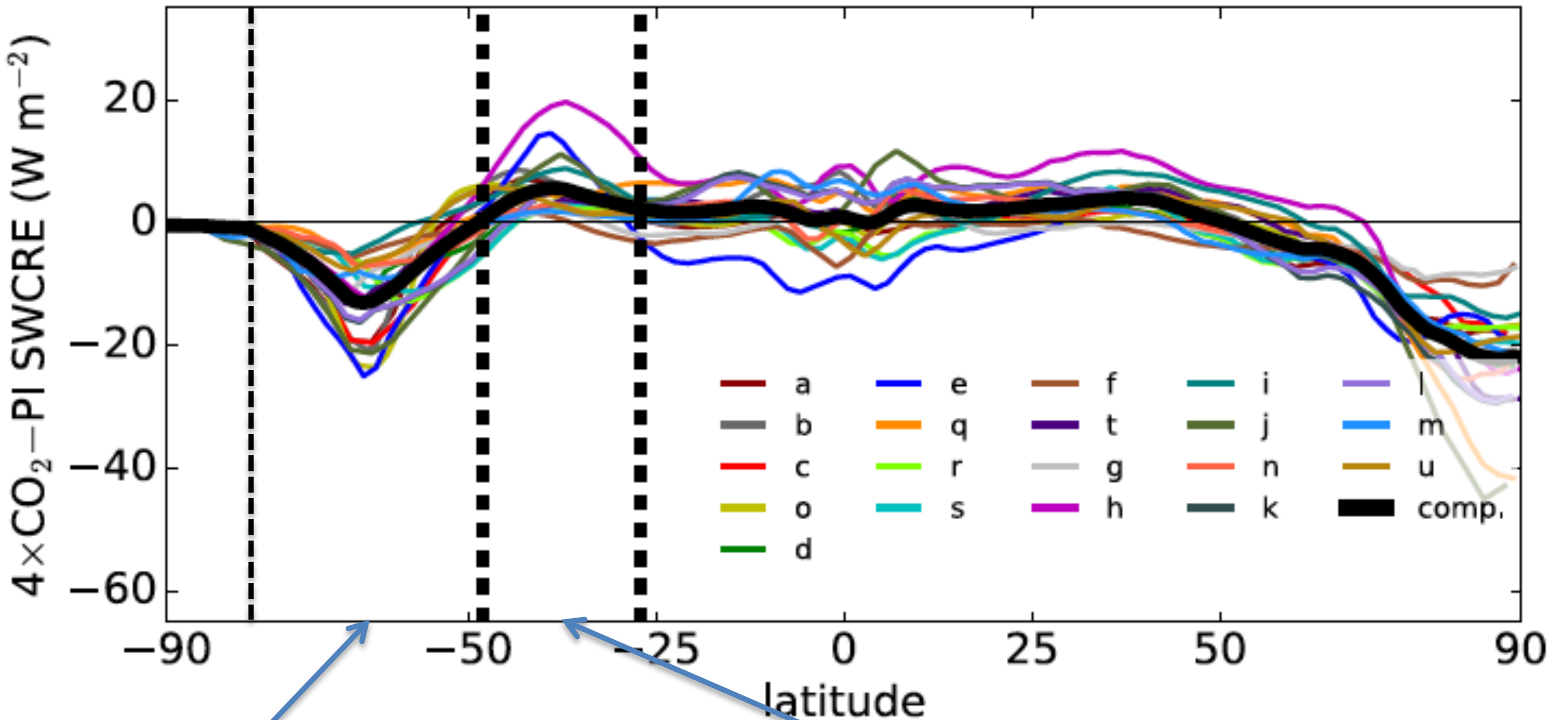

Lipat et al. *2018*

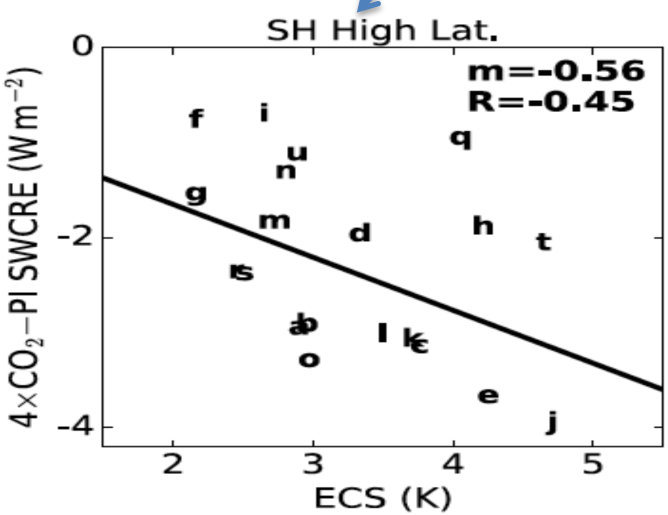
# CMIP5

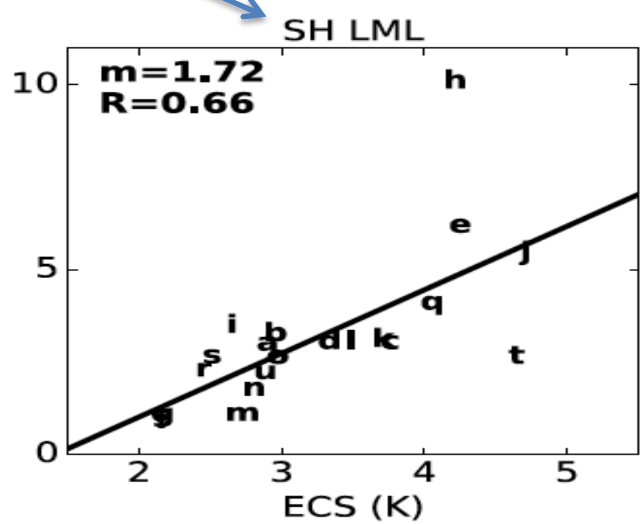



Lipat et al. *submitted*

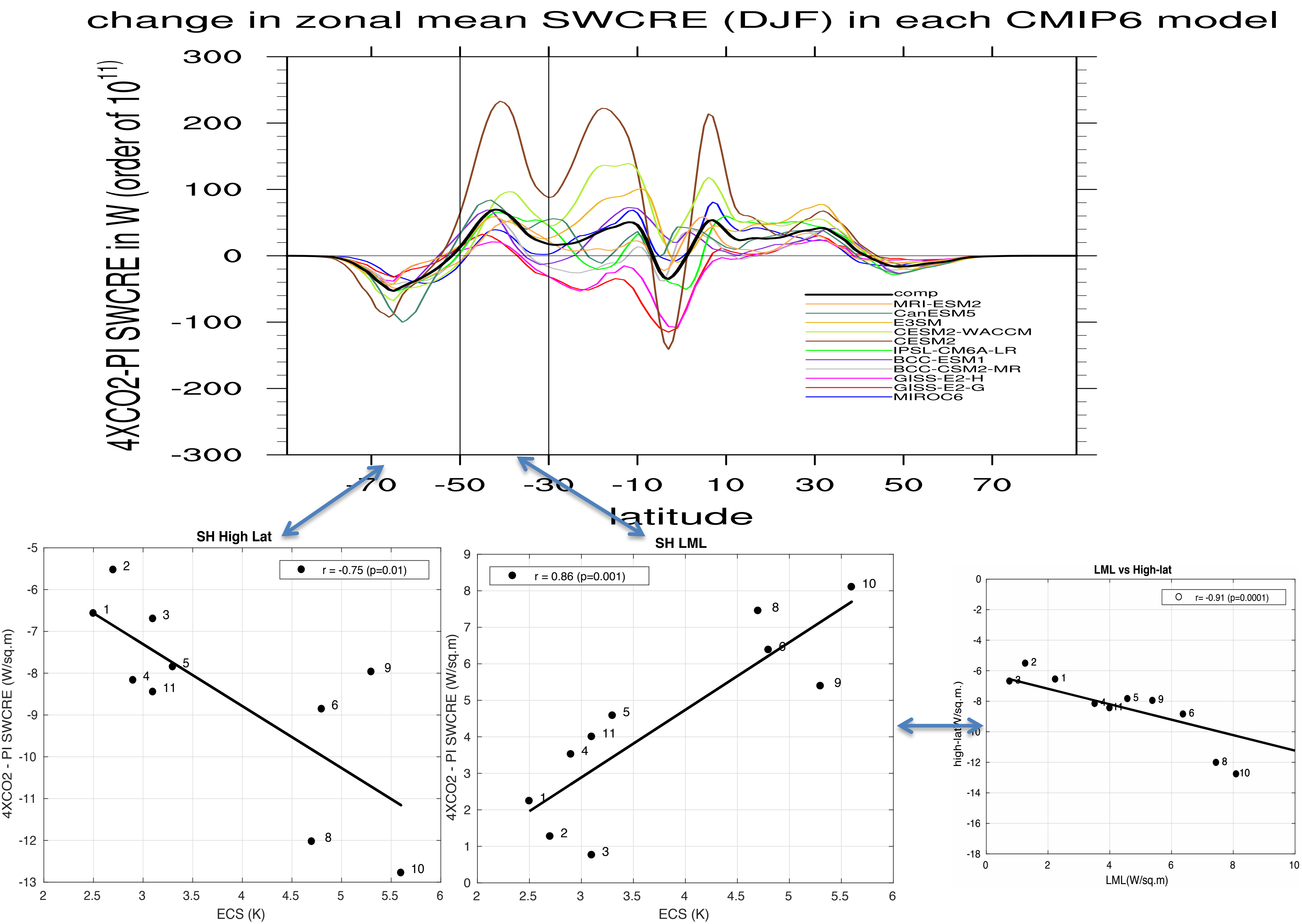
# Annual 4xCO2 SWCRE changes in CMIP5 models and their relation to climate sensitivity



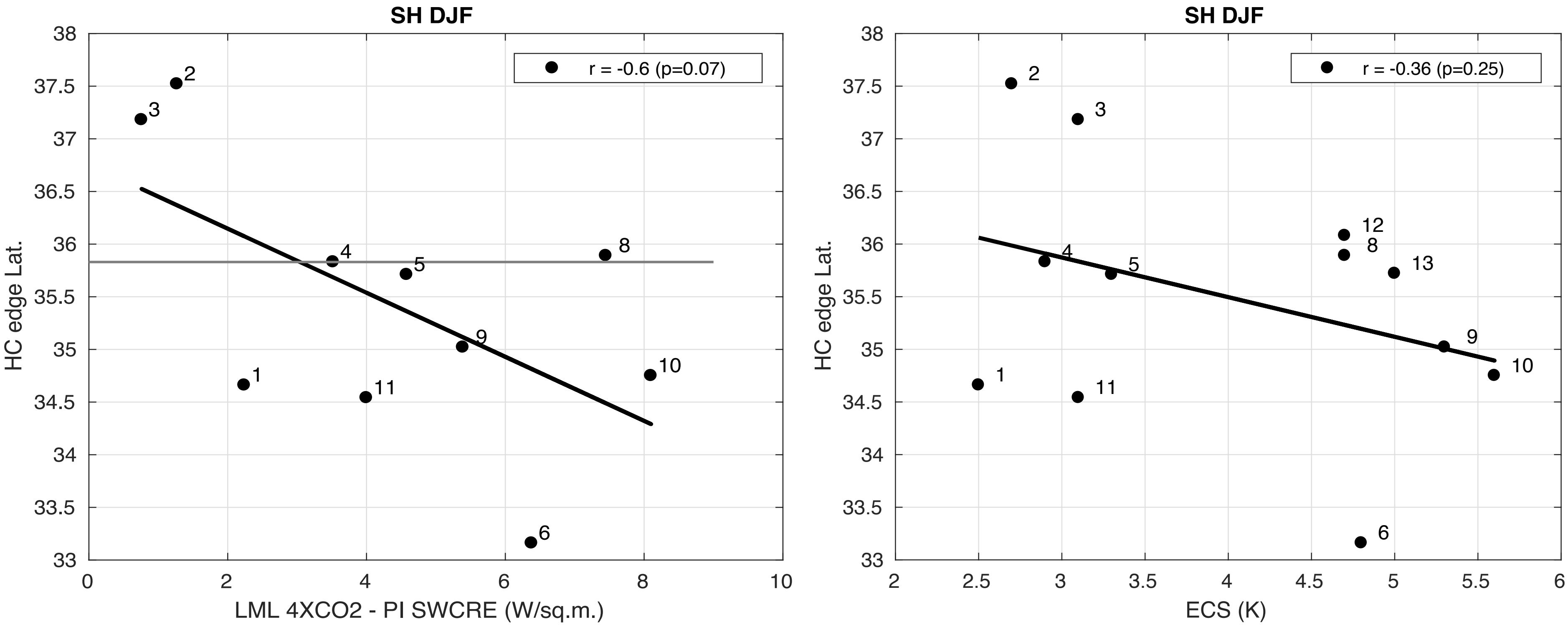




Lipat, Tselioudis, Grise, Polvani, GRL, 2017



change in zonal mean SWCRE (DJF) in each CMIP6 model
4XCO2-PI SWCRE in W (order of 10^11)
latitude
comp
MRI-ESM2
CanESM5
E3SM
CESM2-WACCM
CESM2
IPSL-CM6A-LR
BCC-ESM1
BCC-CSM2-MR
GISS-E2-H
GISS-E2-G
MIROC6
SH High Lat
r = -0.75 (p=0.01)
4XCO2 - PI SWCRE (W/sq.m)
ECS (K)
SH LML
r = 0.86 (p=0.001)
4XCO2 - PI SWCRE (W/sq.m)
ECS (K)
LML vs High-lat
r= -0.91 (p=0.0001)
high-lat (W/sq.m.)
LML(W/sq.m)

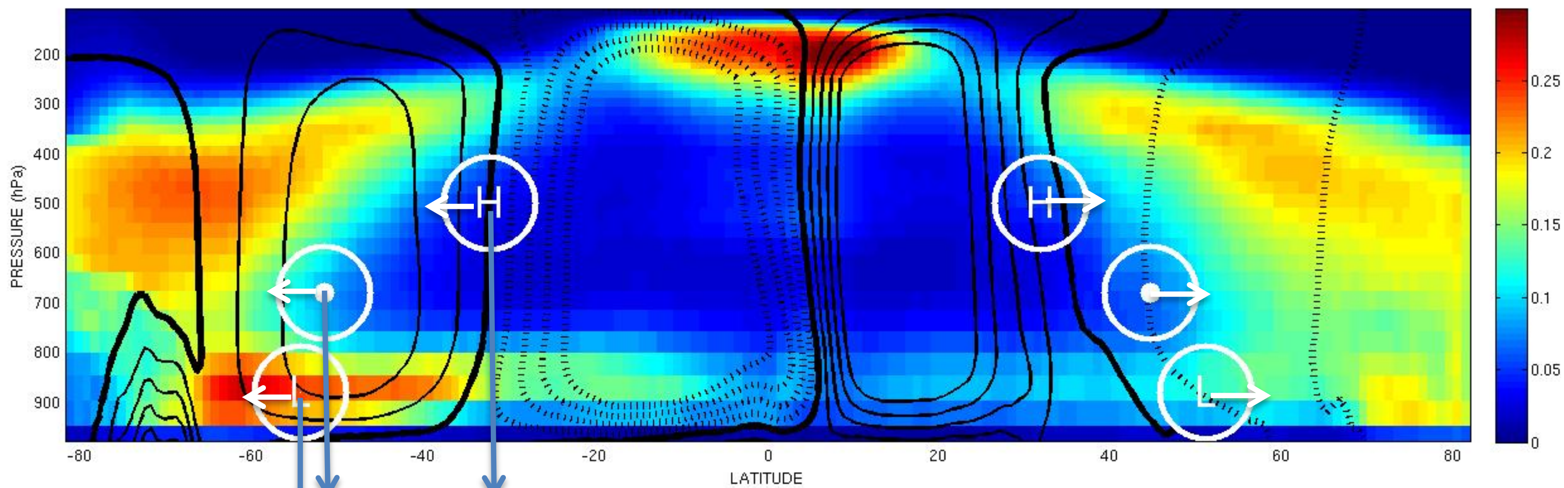



## Preliminary conclusions

- High-ECS CMIP6 models analyzed so far tend to produce larger LML SWCRE warming in 4xCO2 simulations than any CMIP5 model
- This LML SWCRE is weakly correlated to the climatological Hadley cell edge position for this CMIP6 model subset, and the associated ECS values are not correlated to the Hadley cell edge

# What are the cloud/radiation effects of circulation shifts?

CloudSat/CALIPSO cloud vertical profile




U850 max

Hadley cell edge

Storm track

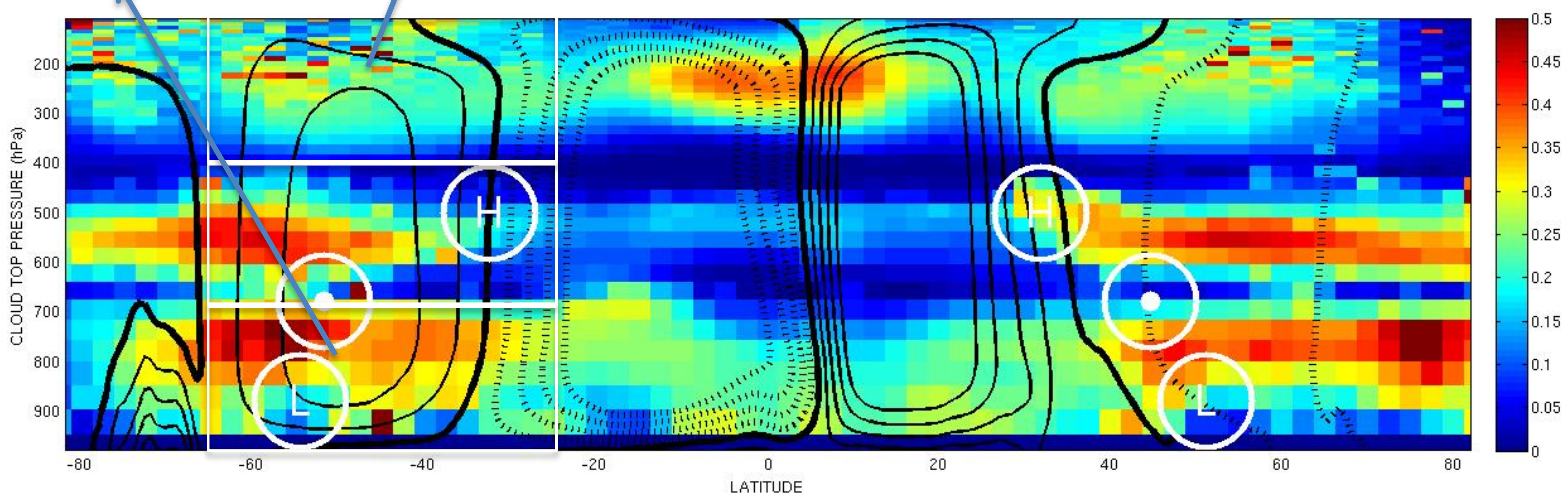
We regressed midlatitude total/high/low-cloud central latitude and mean SWCRE/LWCRE on all major circulation features

Tselioudis, Lipat, Grise, Polvani, 2016

Low cloud Central latitude

High cloud Central latitude

ISCCP cloud top profile



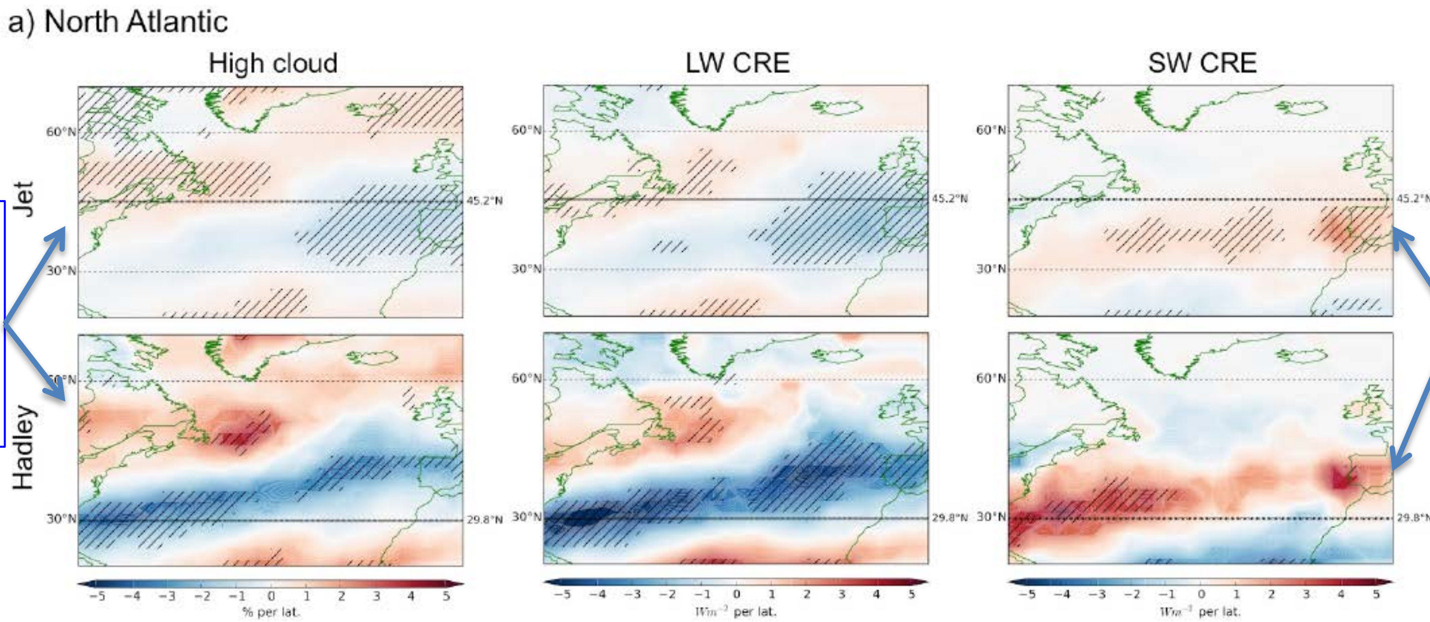
# Regressions between Hadley/Jet shifts and cloud and CRE properties

| | | SH | | | | | N. Atl. | | | | | N. Pac. | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| DJF | | Hadley (°) | | **m=0.54 R=0.58** | Jet (°) | | Hadley (°) | | **m=0.15 R=0.57** | Jet (°) | | Hadley (°) | | m=0.10 R=-0.29 | Jet (°) | |
| | | m | R | | m | R | m | R | | m | R | m | R | | m | R |
| | Total (°) | 0.506 | 0.292 | | 2.320 | 0.060 | 0.820 | 0.367 | | **0.149** | **0.518** | 25.64 | 0.007 | | -0.191 | -0.346 |
| | High (°) | **1.206** | **0.466** | | 2.370 | 0.224 | **1.553** | **0.646** | | **0.464** | **0.555** | 8.475 | 0.100 | | -3.745 | -0.081 |
| | Low (°) | **-0.756** | **-0.441** | | -1.284 | -0.245 | -1.292 | -0.364 | | -0.385 | -0.313 | -3.571 | -0.116 | | -0.632 | -0.236 |
| | SW CRE ($Wm^{-2}$) | **-6.024** | **-0.429** | | **-6.024** | **-0.404** | **3.610** | **0.391** | | **0.622** | **0.583** | -14.09 | -0.104 | | -4.785 | -0.111 |
| | LW CRE ($Wm^{-2}$) | 2.494 | 0.359 | | 4.202 | 0.201 | **-3.247** | **-0.536** | | **-0.898** | **-0.498** | 6.369 | 0.212 | | 14.93 | 0.032 |
| JJA | | Hadley (°) | | m=0.15 R=0.17 | Jet (°) | | Hadley (°) | | m=0.37 R=0.31 | Jet (°) | | Hadley (°) | | m=0.33 R=0.39 | Jet (°) | |
| | | m | R | | m | R | m | R | | m | R | m | R | | m | R |
| | Total (°) | 1.148 | 0.239 | | -1.745 | -0.098 | 0.545 | 0.289 | | -2.494 | -0.074 | 0.259 | 0.339 | | 0.340 | 0.224 |
| | High (°) | **1.938** | **0.490** | | 9.804 | 0.061 | **0.450** | **0.522** | | 2.110 | 0.131 | **0.591** | **0.395** | | 0.793 | 0.254 |
| | Low (°) | **-1.140** | **-0.630** | | -1.672 | -0.268 | -2.273 | -0.103 | | -1.852 | -0.149 | 0.549 | 0.283 | | 0.902 | 0.149 |
| | SW CRE ($Wm^{-2}$) | **-2.857** | **-0.405** | | -3.195 | -0.226 | -41.70 | -0.021 | | 3.205 | 0.311 | -11.49 | -0.117 | | 3.279 | 0.353 |
| | LW CRE ($Wm^{-2}$) | 8.000 | 0.187 | | 5.747 | 0.162 | -6.623 | -0.052 | | -1.230 | -0.329 | 3.378 | 0.137 | | -1.076 | -0.371 |

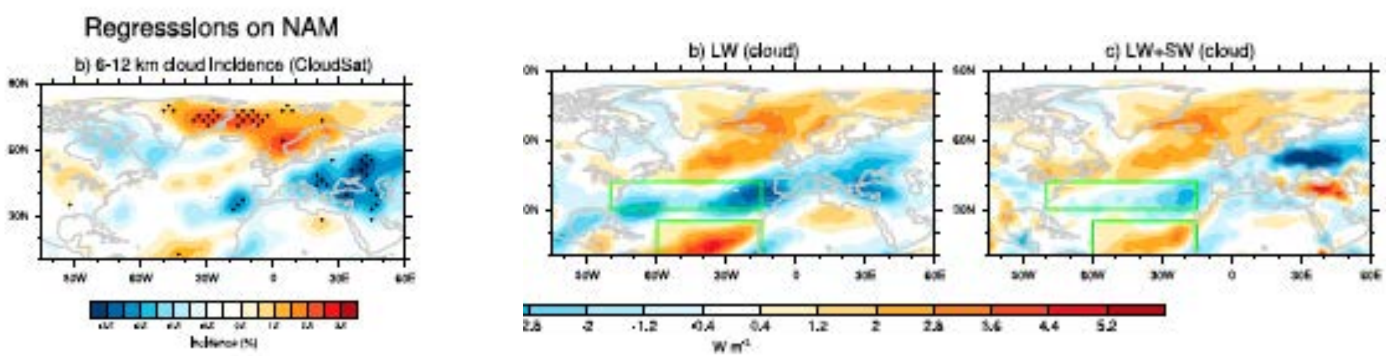
- Only Dynamics-Clouds pair coherently shifting in (almost) all basins/seasons is Hadley-High Cloud
- Jet shifts coherently with High Cloud only in N. Atlantic - DJF
- High Cloud-Jet/Hadley poleward shifts in N. Atlantic – DJF produce SW warming, while High Cloud-Hadley poleward shifts in S. Ocean DJF/JJA produce SW cooling

# Cloud/radiation changes with poleward Hadley/jet shifts

The pulling of the high-cloud curtain….

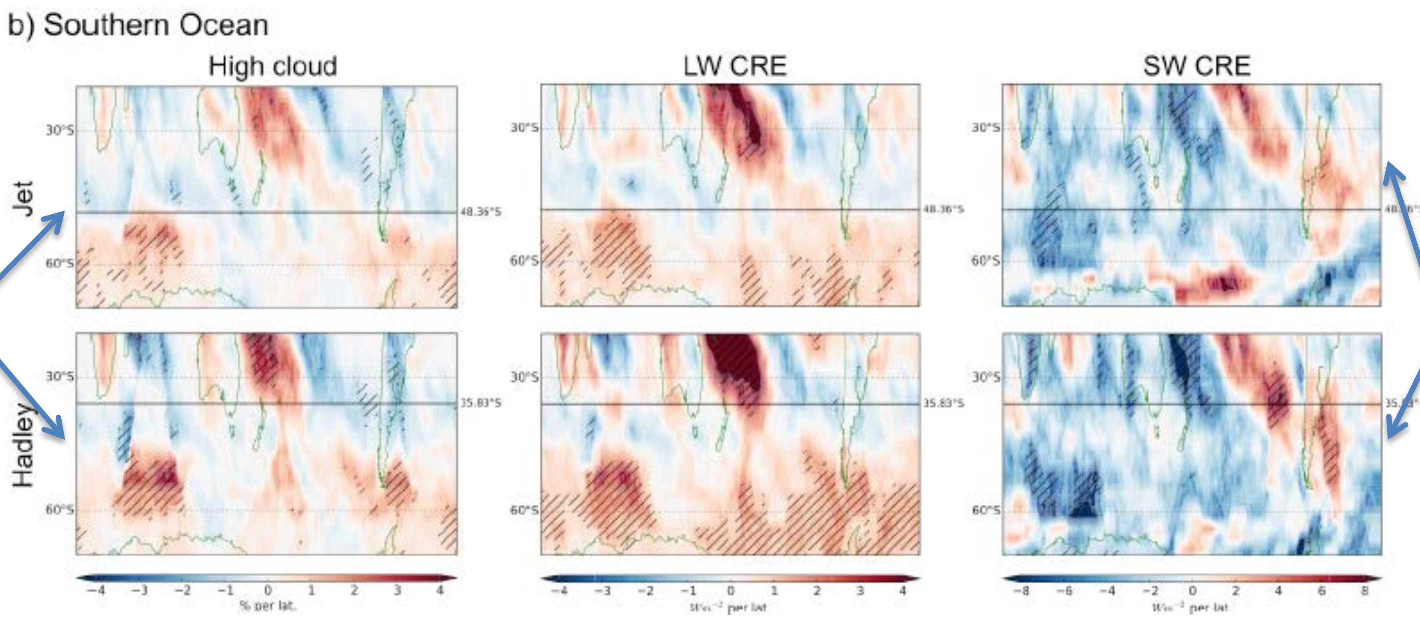



….lets more solar flux in the lower midlatitude regions



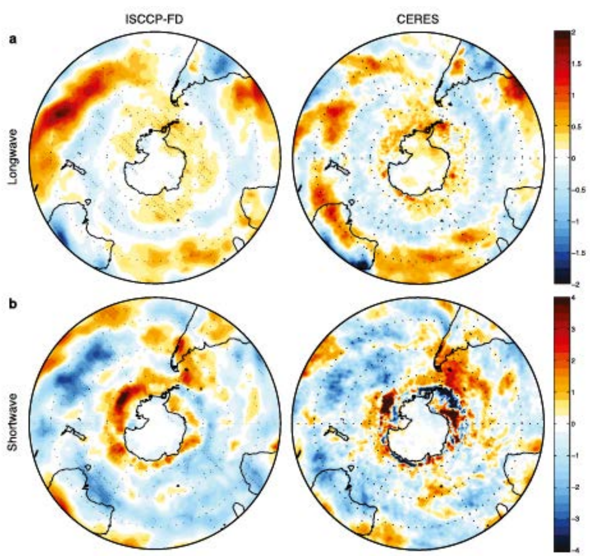

Li, Thompson, Huang, Zhang, 2014

# Cloud/radiation changes with poleward Hadley/jet shifts

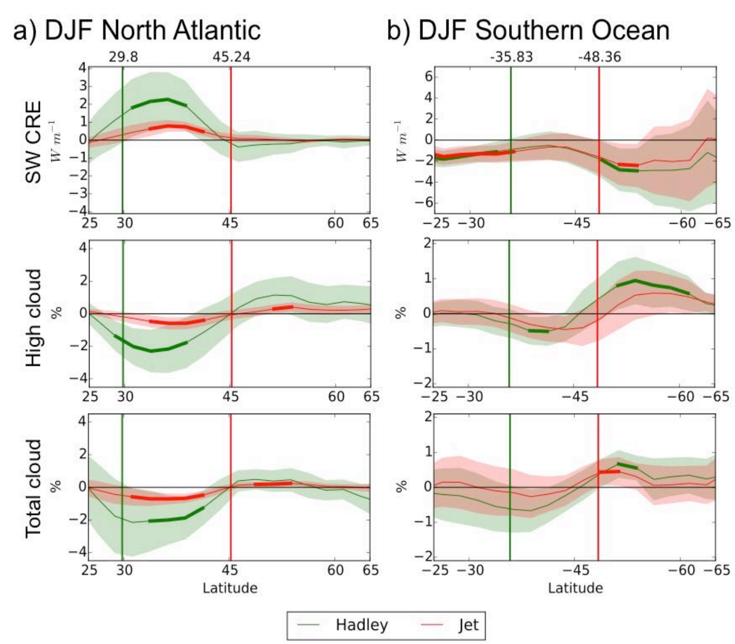



The high-cloud curtain is still pulled....

....but the lower midlatitude solar flux does not increase



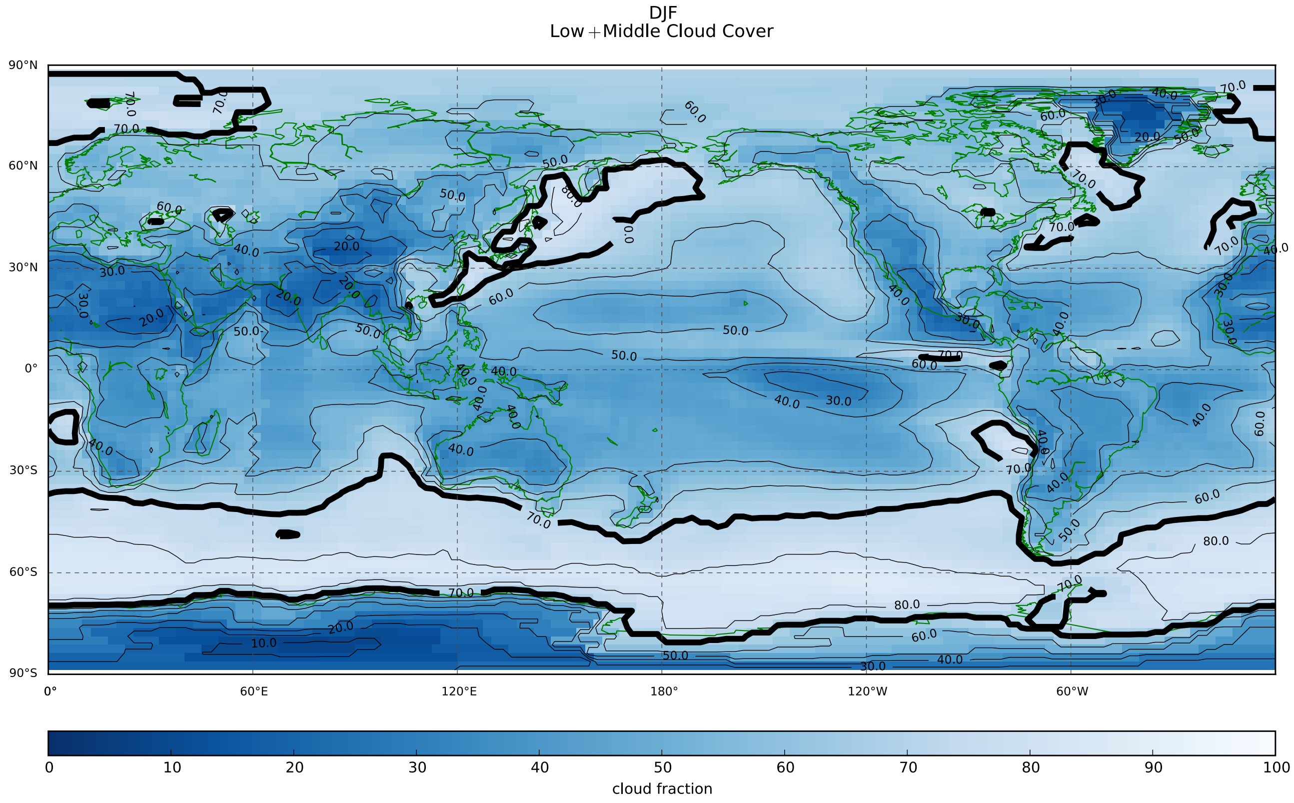

High cloud shift – Total cloud decrease – SW warming




High cloud shift – No Total cloud change – weak SW cooling

Grise and Polvani, 2014

# Global Low + Middle cloud cover in DJF

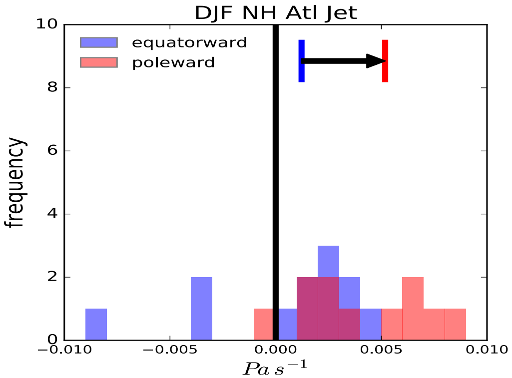



High clouds in the Southern Ocean are embedded in a cloud field of very high low- and middle-cloud amounts – High cloud shifts have small effect on total cloud cover

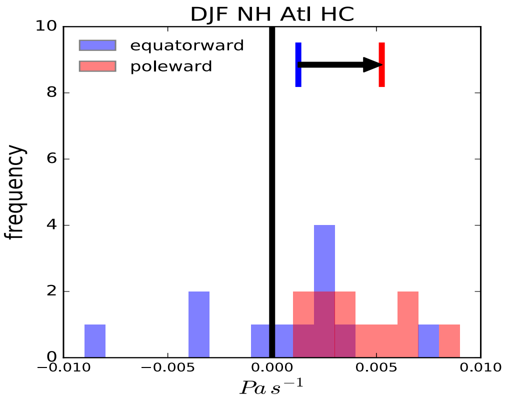
# Omega changes with Jet and Hadley shifts

## N. Atl. 30-45N DJF

### Jet

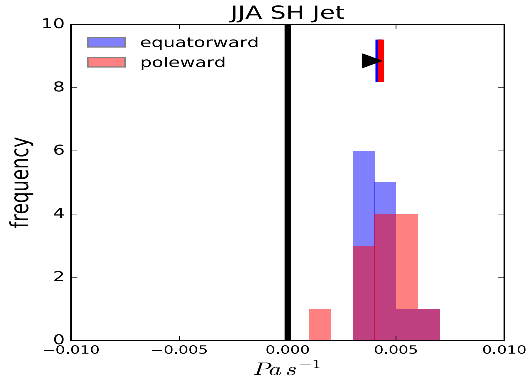



### Hadley

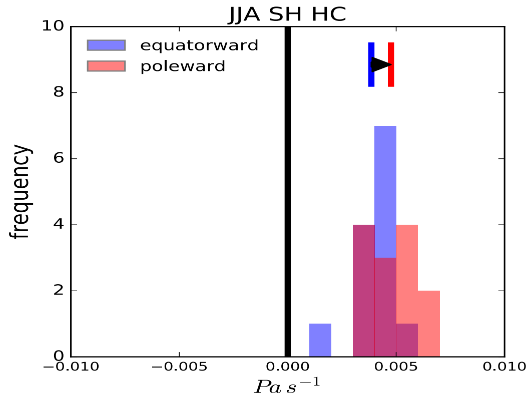



## S. Ocean 30-45S JJA

### Jet




### Hadley

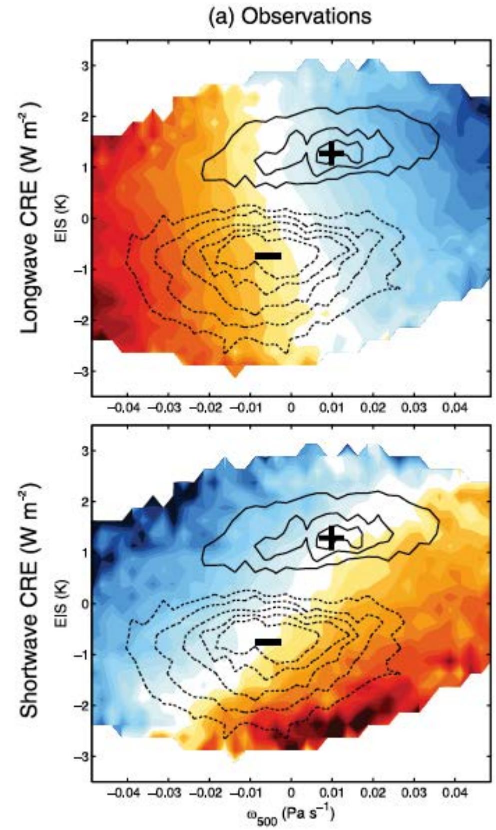



In the N. Atlantic winter, Jet and Hadley shifts correspond to large omega changes, while in the Southern Ocean winter the omega changes from such shifts are small

# CRE changes with omega/EIS

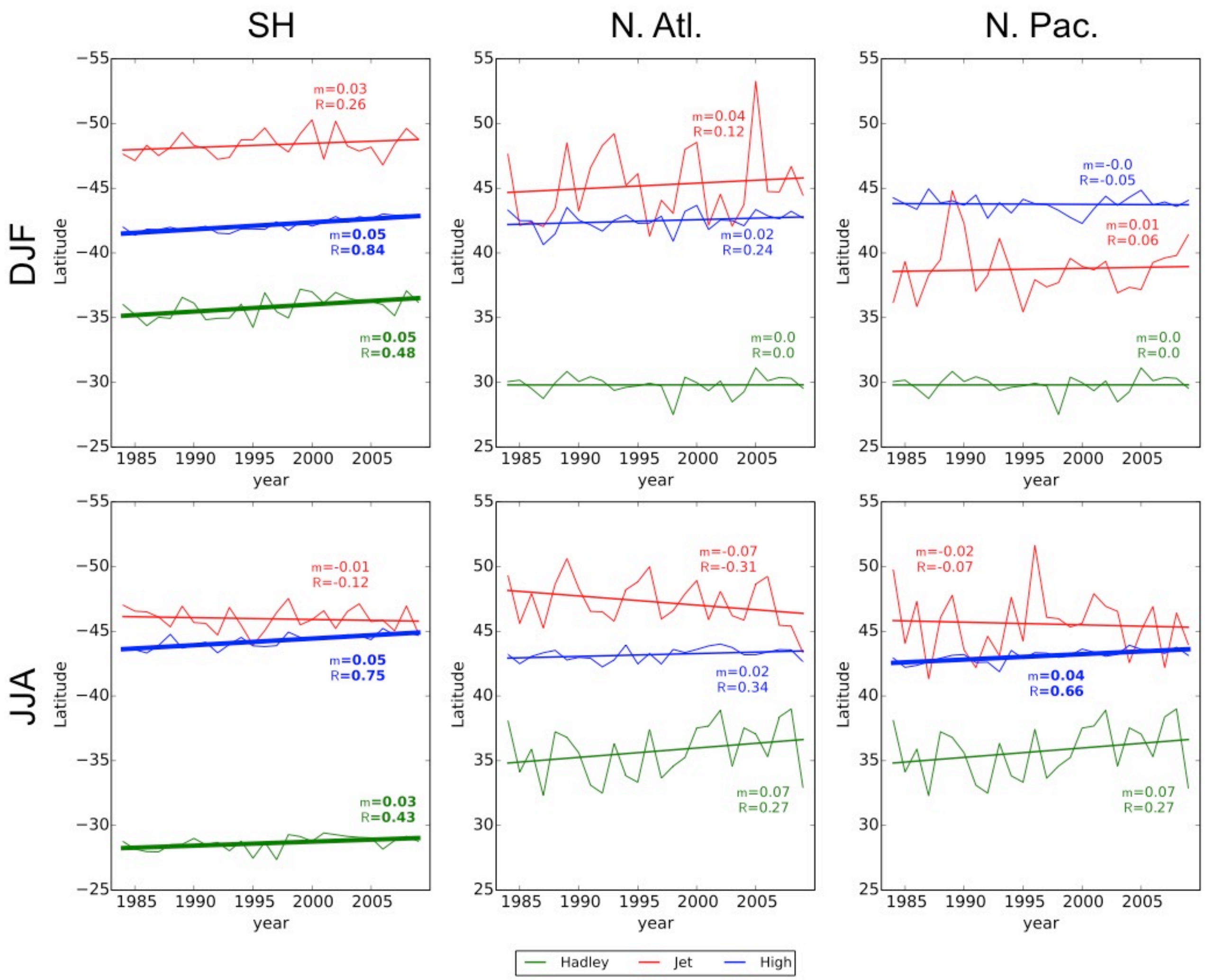
Grise and Madeiros 2016

## S. Ocean 40-50S




LWCRE varies primarily with omega, while SWCRE variability is dependent on both omega and EIS

## High cloud, Hadley, and Jet shifts in the 1983-2009 period




- Hadley cell and high clouds have been shifting consistently poleward at rates of 0.3-0.5 degrees/decade in the Southern Hemisphere

- Hadley cell expansion would be the primary culprit for the observed cloud poleward shifts

# Discussion

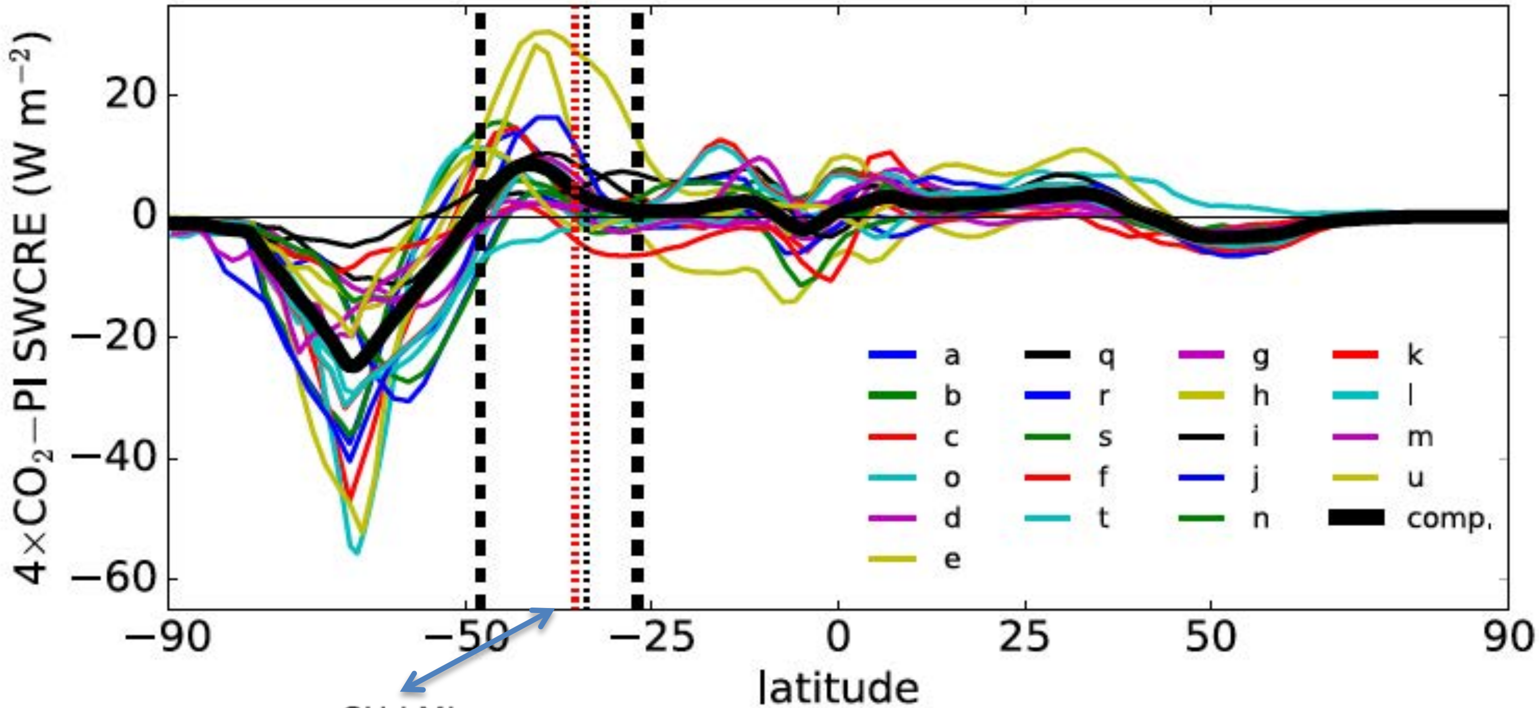
- Hadley cell extent correlates strongly with high cloud shifts in almost all basins and seasons. Storm track or eddy jet location show weaker correlations with high cloud, mostly in the winter seasons.

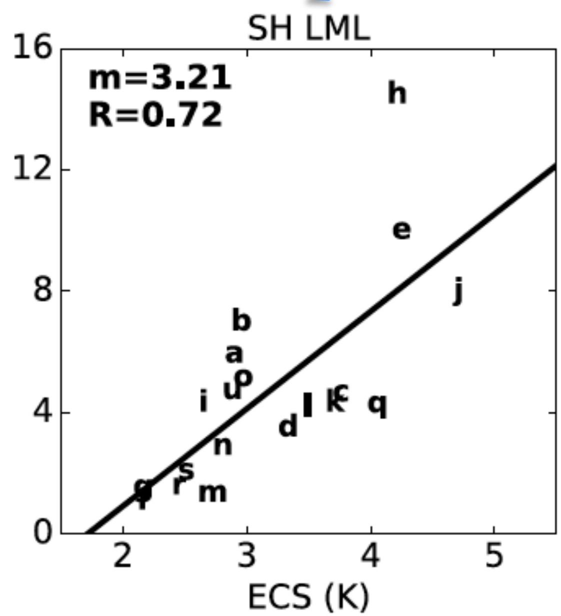
- Radiative effects of cloud shifts are complex and vary with latitude and season. LW CRE shows expected warming/cooling dipole with poleward high cloud shifts. SW CRE shows subtropical warming with Hadley/jet shifts in the N. Atl. but cooling almost everywhere in the Southern Ocean. Lack of S. Ocean warming with the high cloud shifts may be due to weak vertical velocity response and/or large cloud amount of the background low and middle cloud field.

- The high cloud poleward shift observed in ISCCP in the 83-09 period can be attributed to Hadley cell expansion rather than jet poleward shift.

- **Question now is, how do models simulate those coherent dynamics-clouds-radiation shifts, and do those shifts matter to model climate sensitivity**

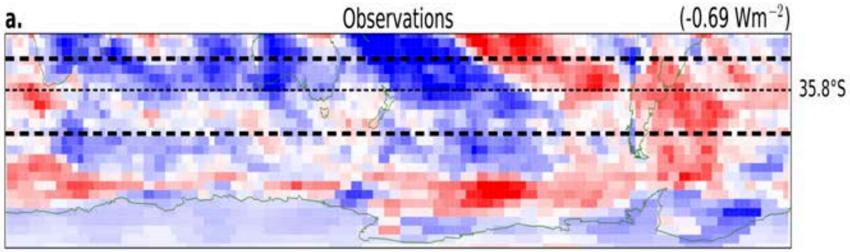
# DJF 4xCO2 SWCRE changes in CMIP5 models and their relation to climate sensitivity



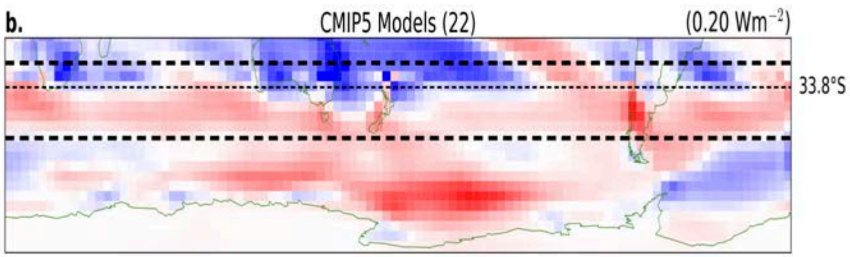



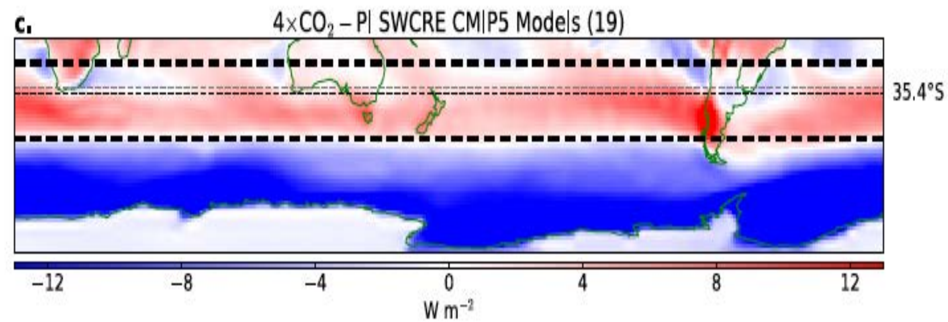

DJF SWCRE warming in 4xCO2 CMIP5 model runs correlates strongly with model ECS

## Observational and model control run SWCRE response to 1-degree poleward HC shift




## CMIP5 model SWCRE change in 4xCO2 experiments



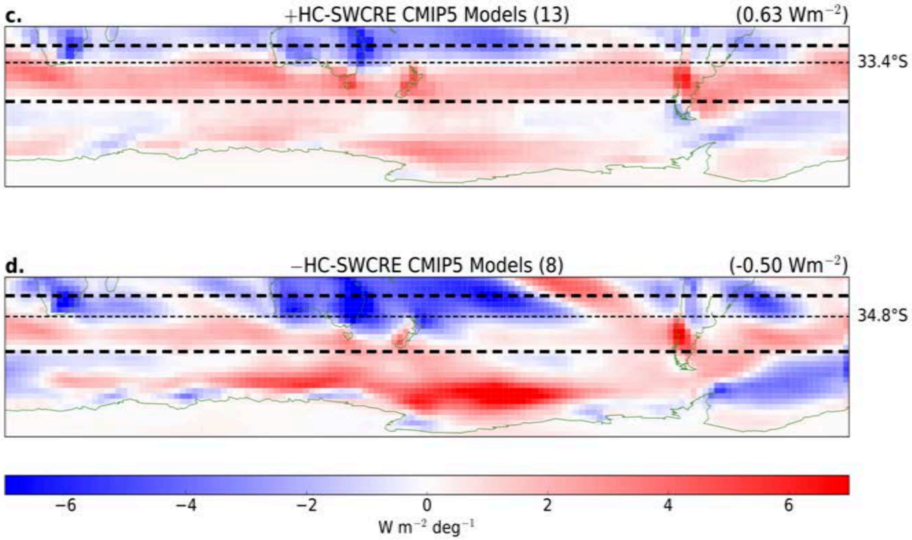

Unlike the observations, model control runs show a zone of SWCRE warming in the SH LML region when HC edge shifts poleward.

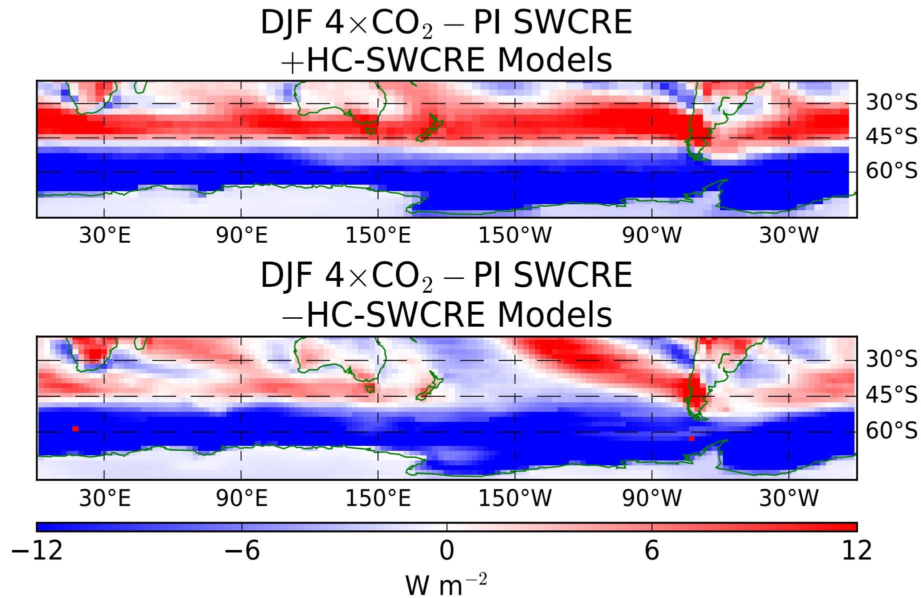
Zone of 4xCO2 SW warming in the Lower Midlatitudes, with patterns similar to the warming from poleward HC shift in the control runs

Lipat, Tselioudis, Grise, Polvani, GRL, 2017

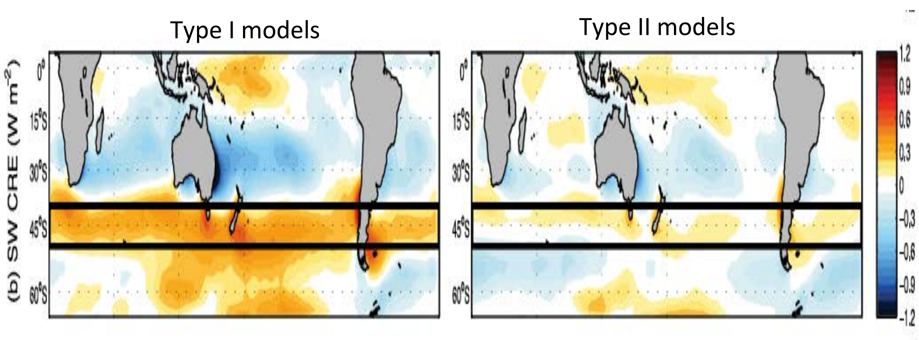
Models that in control runs warm strongly the LML region with poleward HC shifts....

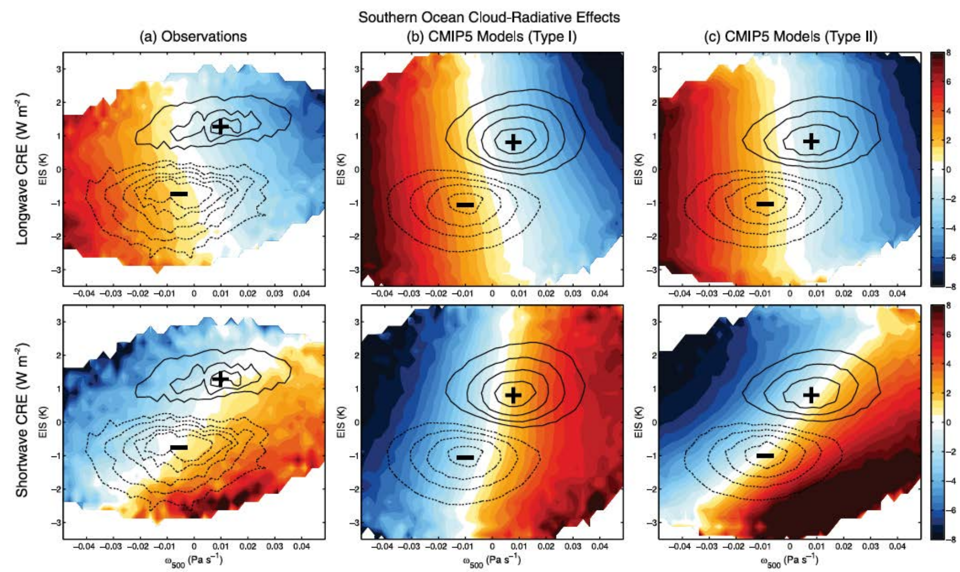
...are the models that warm strongly the LML region in 4xCO2 simulations......




....but also the models with the more narrow climatological Hadley cells

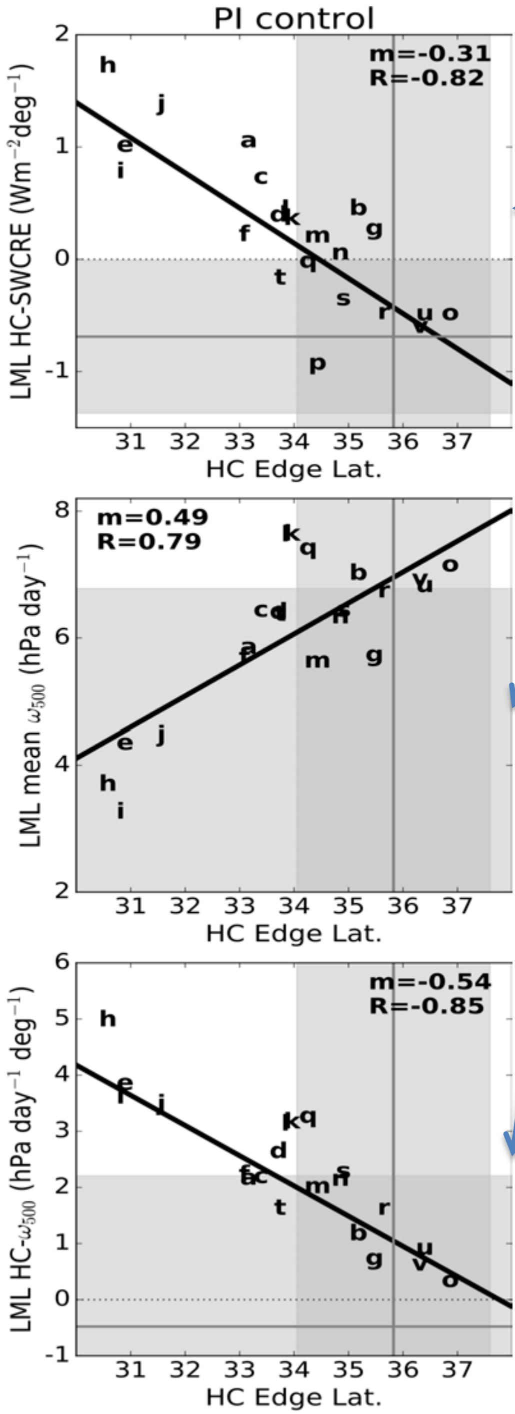



Similar separation of Type I-II models based on SWCRE warming with poleward jet shifts

Attributed to differences in the dependence of SWCRE on omega and EIS

Grise and Madeiros 2016

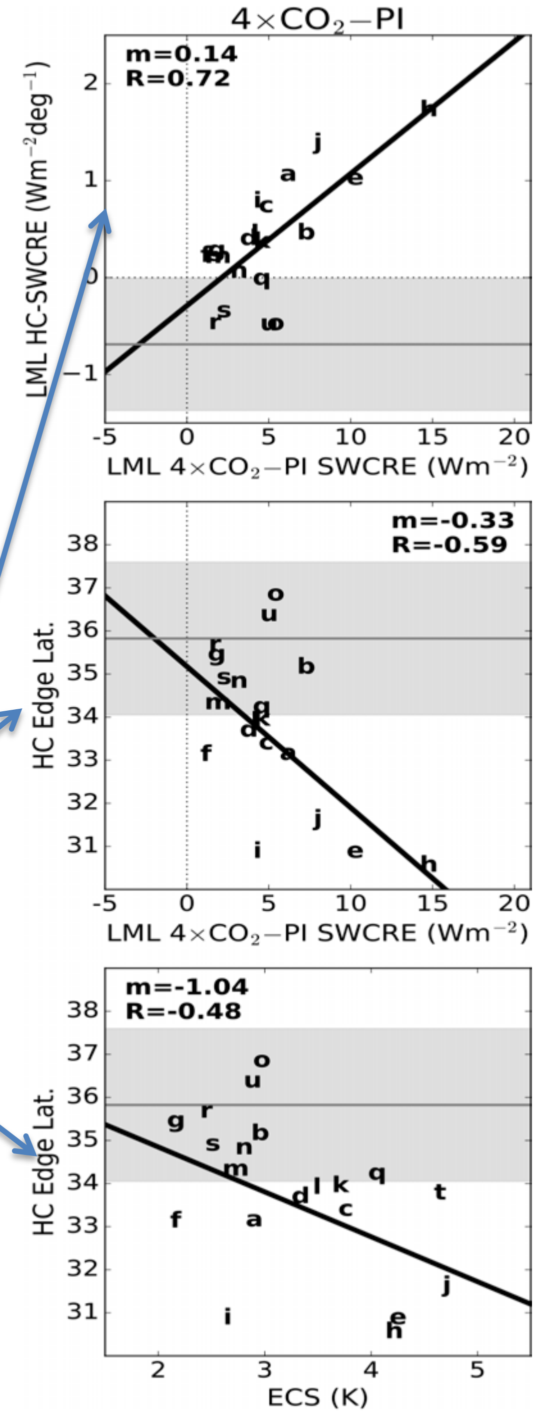


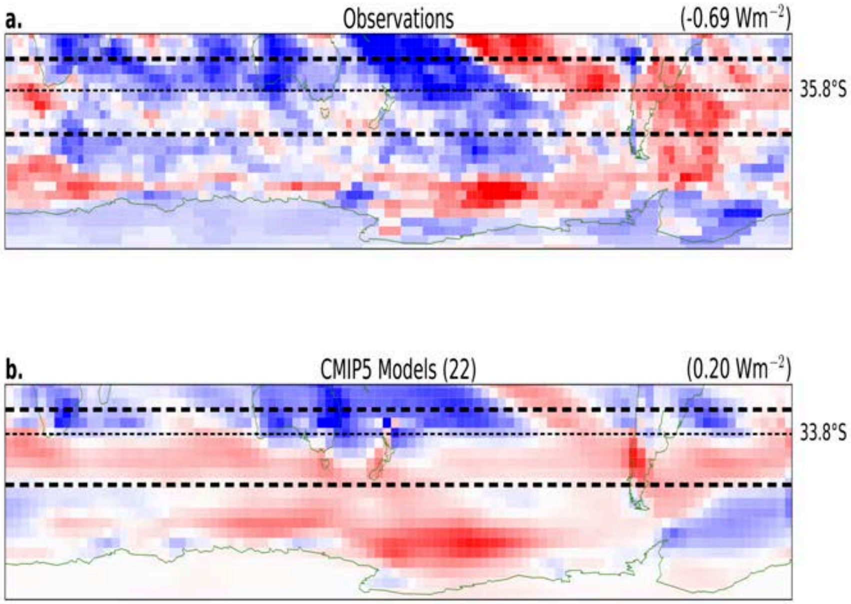

<u>In Pre-Industrial control runs:</u>

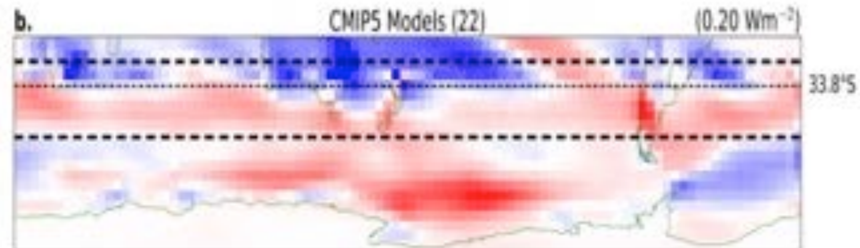
- Changes in LML SWCRE with poleward Hadley cell shift correlate strongly with HC edge climatological position
- This is because LML mean subsidence is weaker in models with more narrow HC, and their subsidence change is larger when the HC edge shifts poleward

<u>In 4xCO2 runs:</u>

- LML SWCRE warming is significantly predicted by control SWCRE change with poleward HC shift and, thus, by climatological HC edge position
- ***Therefore, ECS is significantly constrained by the climatological HC edge position, and models with more realistic HC edge positions tend to have lower ECS values***




a.
Observations
(-0.69 Wm$^{-2}$)
35.8°S
b.
CMIP5 Models (22)
(0.20 Wm$^{-2}$)
33.8°S


b.
CMIP5 Models (22)
(0.20 Wm$^{-2}$)
33.8°S

*Lower midlatitude warming in CMIP5 models shows dependence on climatological HC circulation, but may also be related to the mechanics of the cloud-dynamics interactions*

**Question**

To what extent does climatological circulation control model differences in cloud-circulation coupling?

***How*** **to Answer**

Compare cloud-circulation coupling in “climates” where only difference is climatological circulation

***Tool*** **to Answer**

ECHAM6: general circulation model in idealized aqua-planet configuration with 10m slab ocean

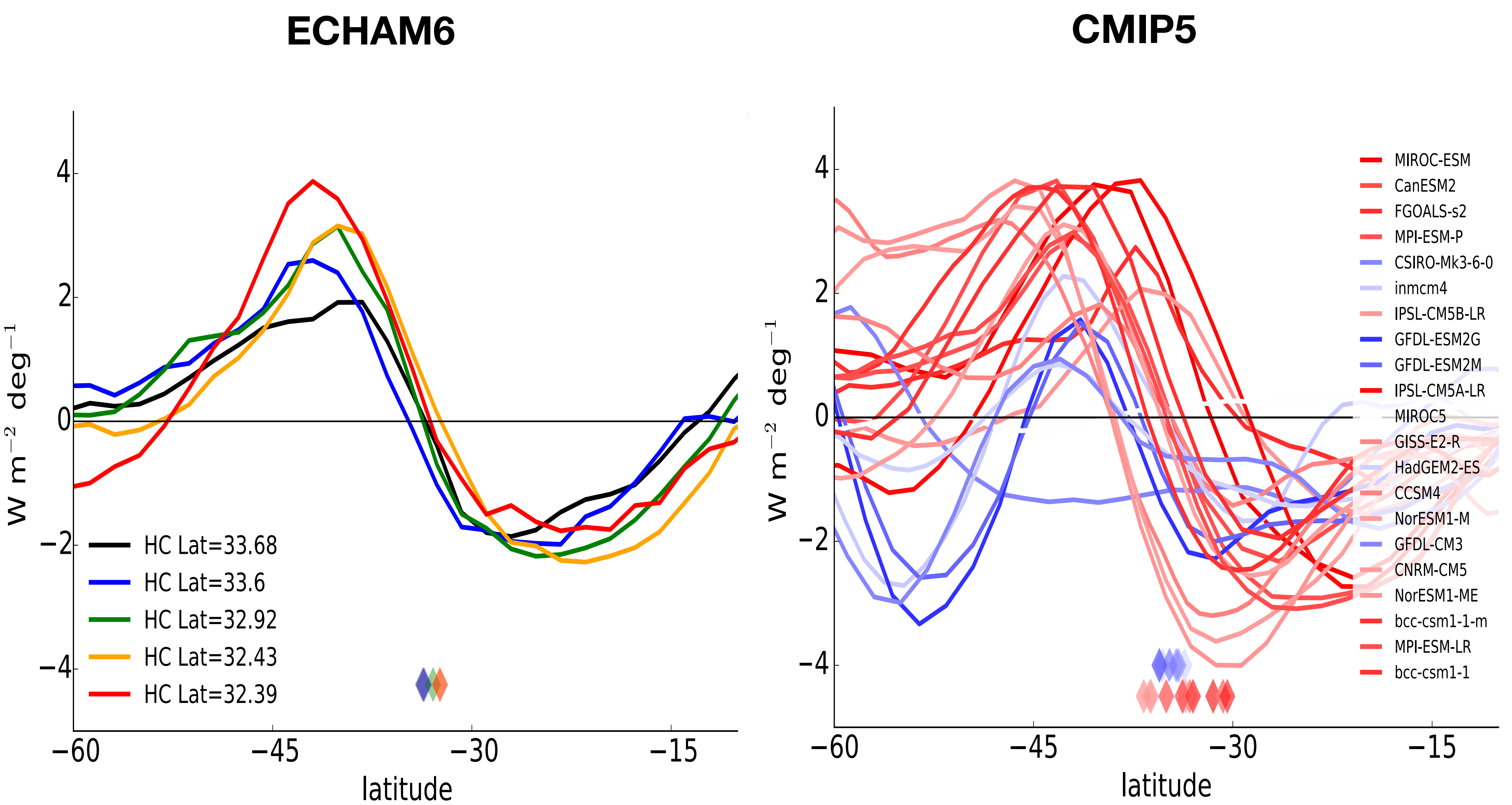
***Method***

Vary model HC edge latitude by varying value of boundary layer drag, and compare cloud-circulation coupling between the different model runs

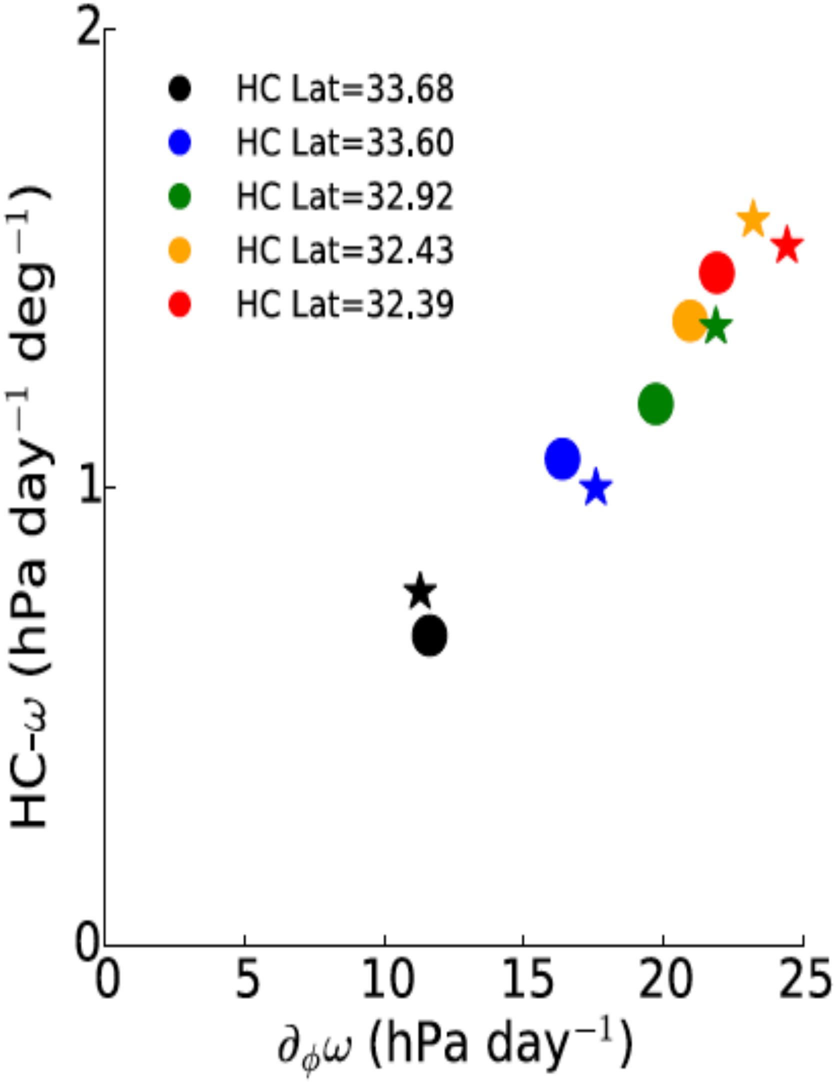


Lipat, Voight, Tselioudis, Polvani, 2017, submitted

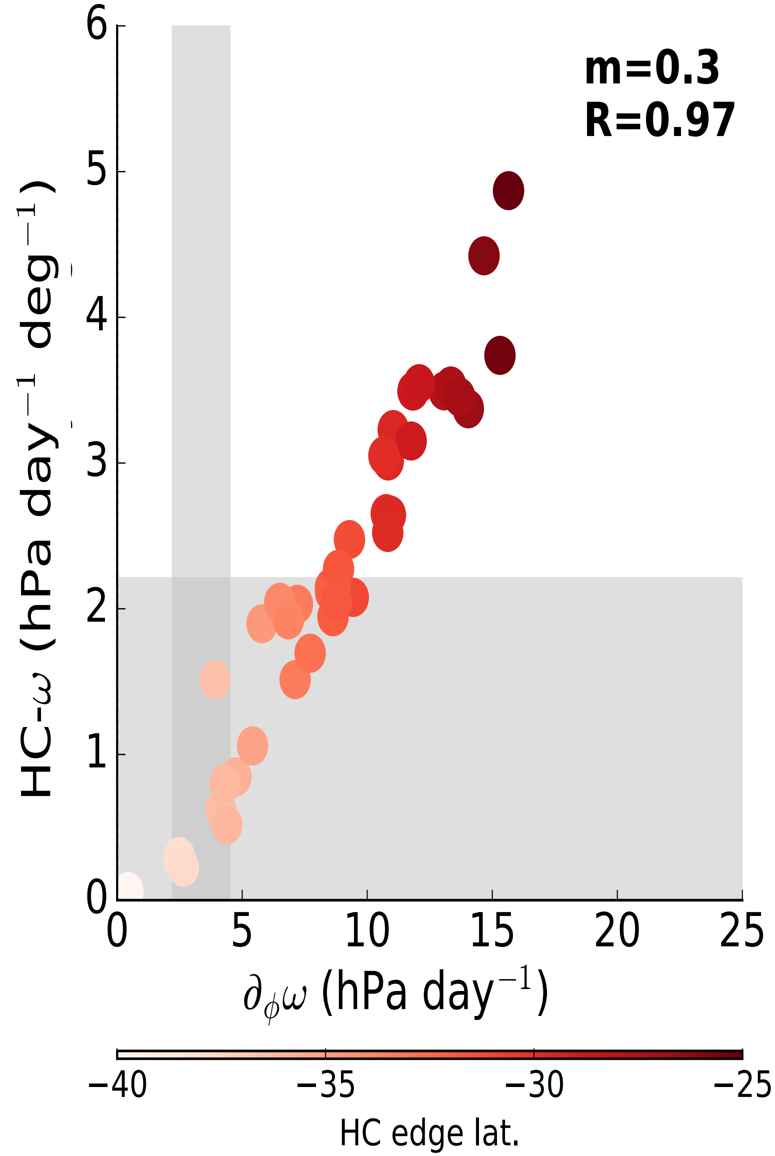
# SWCRE change with HC shift in ECHAM6 and in CMIP5 models



## ECHAM6




## CMIP5




Lipat et al. *2018*

# Discussion

- Spread in model differences in midlatitude cloud-circulation coupling is significantly constrained by model climatological circulation

- Climates with narrower vs. wider HCs exhibit stronger HC-induced SWCRE warming…..
- …..resulting from subsidence warming of boundary layer that “burns away” low cloud…….
- …..and is stronger for narrower HCs due to larger omega gradients

- Improving models’ climatological circulation can remove this bias, thus constraining mid-latitude SWCRE feedback

# Overall Remarks

- HC expansion a dominant feature in midlatitude circulation-cloud-radiation feedback loop

- Observational analysis of HC expansion (or jet poleward shift) indicates weak SW warming in the lower midlatitude region of the Southern Ocean

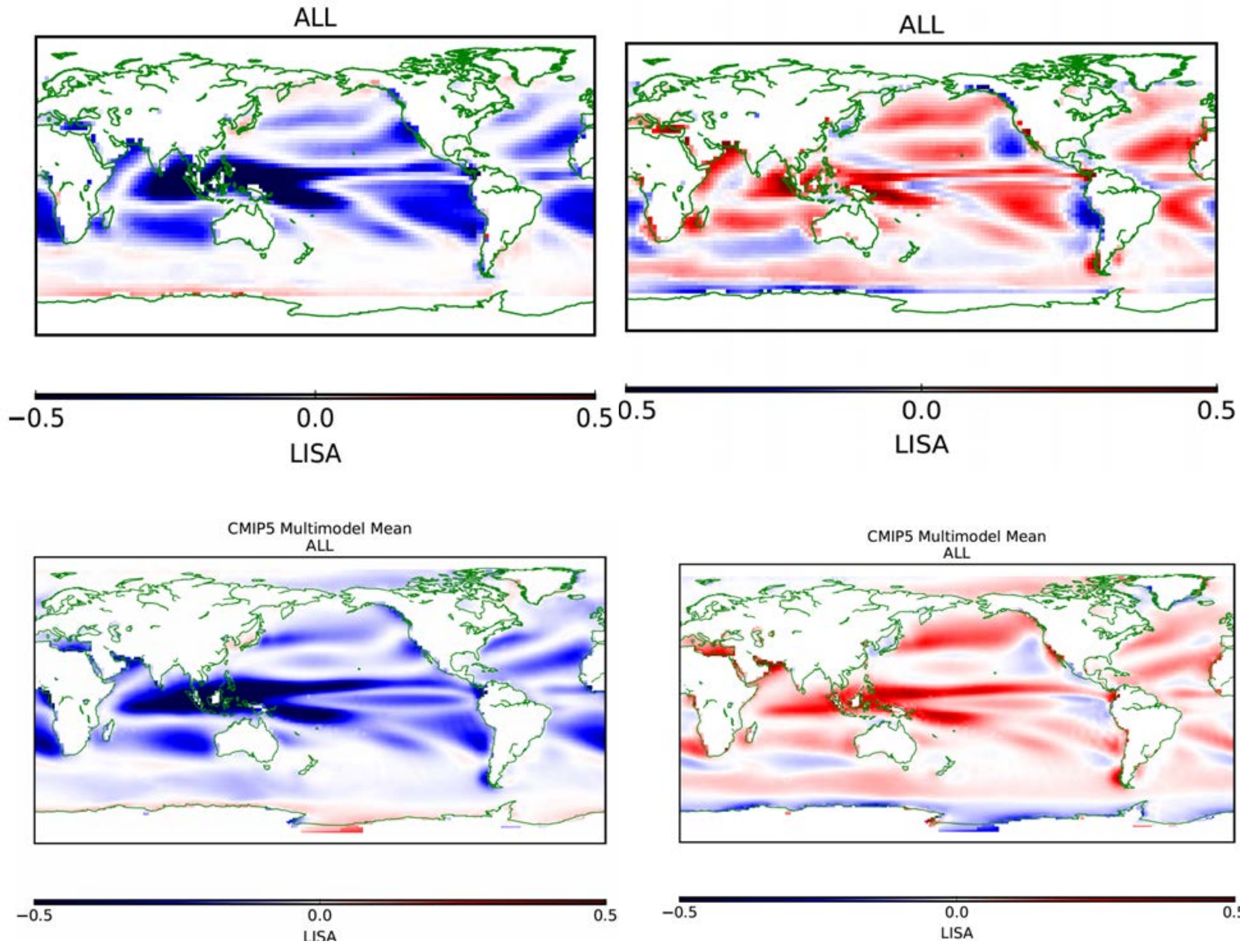
- Models, for the most part, simulate lower midlatitude SW warming with poleward HC expansion and, therefore, with climate warming

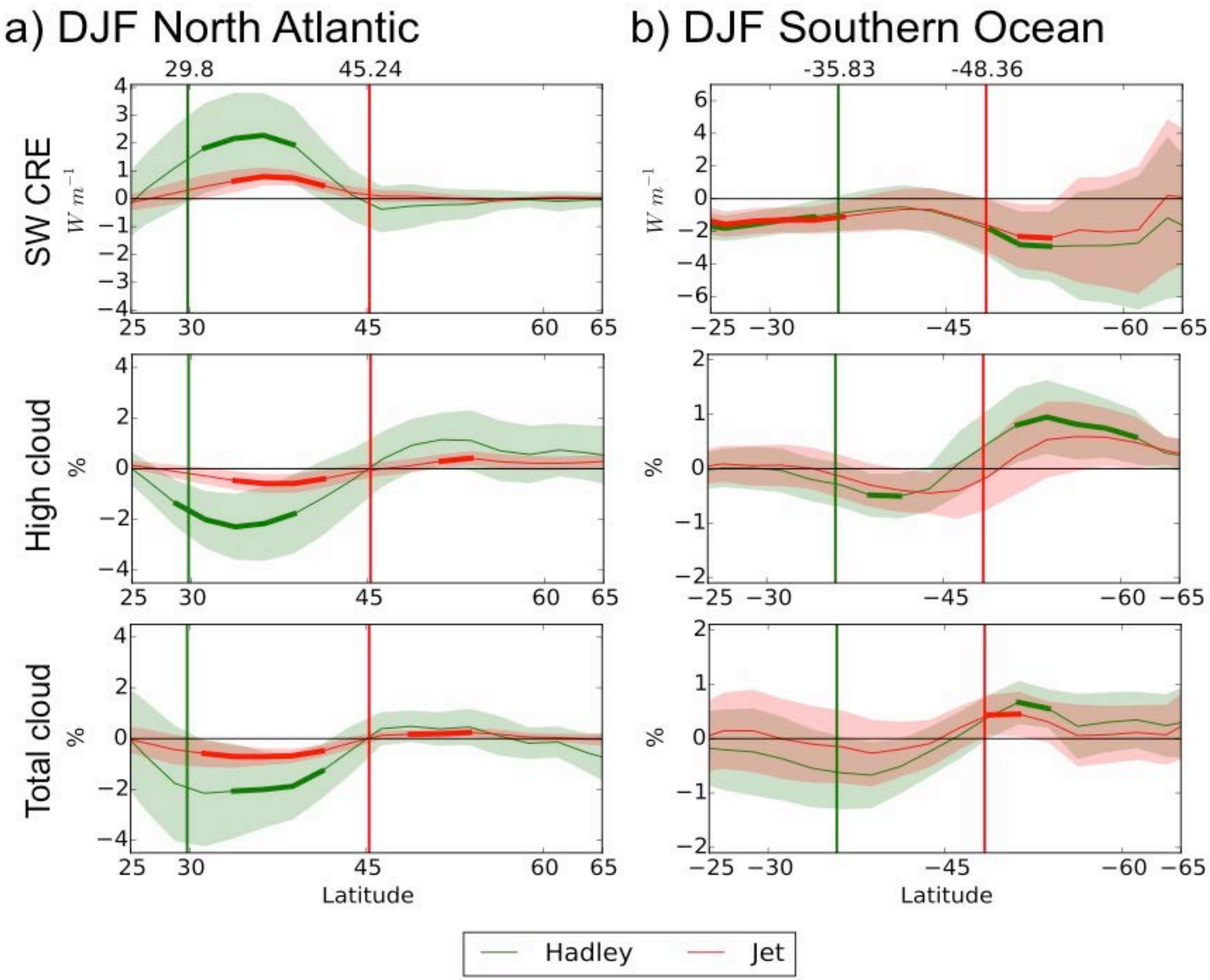
- Amount of LML SWCRE warming depends on climatological HC position, which affects the mean and the change of the LML subsidence

- Models with wider, more realistic Hadley cells tend to produce smaller SW LML warming in climate warming simulations, and thus have lower climate sensitivities

# Local Indicator of Spatial Association (LISA)

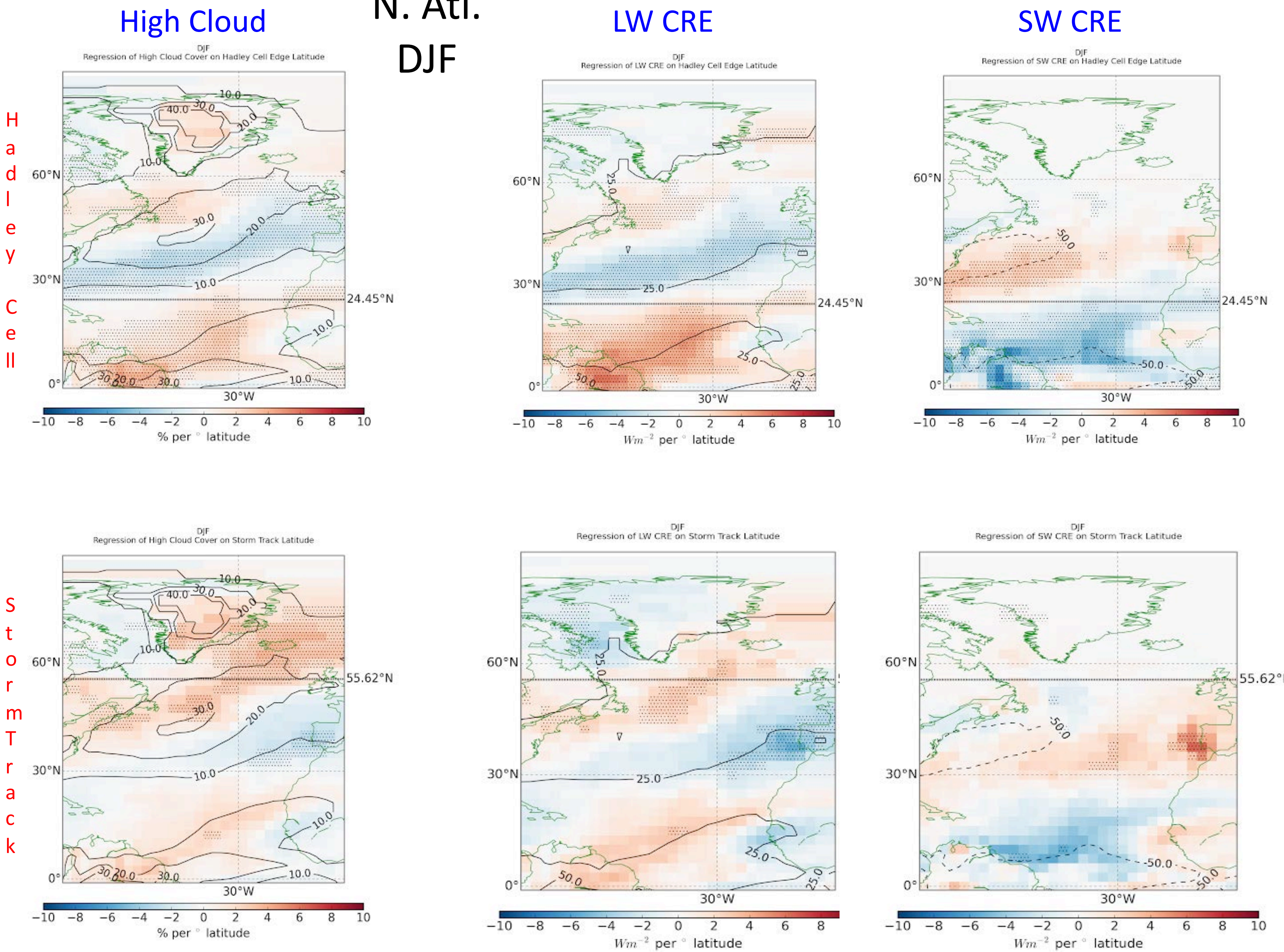
| | LWCRE | SWCRE |
|---|---|---|
| w 500 | **-0.0927** | **0.0395** |
| sfc. u | **0.0251** | **-0.0755** |
| u500 | **-0.0108** | **-0.0599** |
| sfc. v | **-0.0205** | **0.0131** |
| v850 | **-0.0100** | **0.0038** |
| sfc.LHF | **-0.0109** | **-0.0223** |
| sfc. SHF | **-0.0025** | **0.0039** |
| BLH | **-0.0089** | **-0.0129** |
| q500 | **0.0820** | **-0.0096** |
| q1000 | **0.0294** | **0.0241** |
| RH850-RH1000 | **-0.0575** | **-0.0053** |
| RH850 | **0.0425** | **-0.0076** |
| RH1000 | **0.0041** | **-0.0126** |
| T850 | **0.0131** | **0.0137** |
| EIS | **-0.0190** | **0.0051** |
| SST | **0.0164** | -0.0004 |

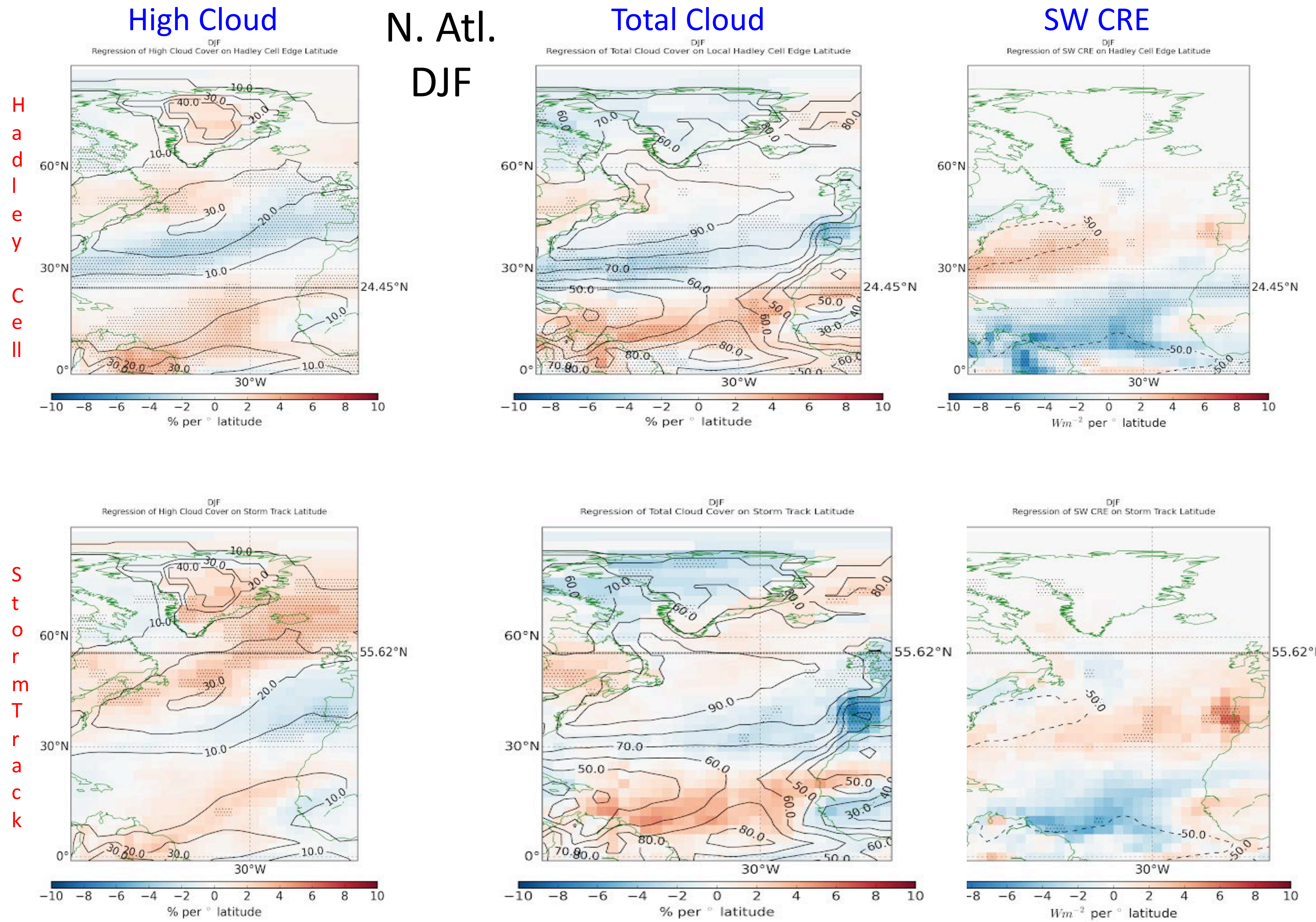




a) DJF North Atlantic
b) DJF Southern Ocean
29.8
45.24
-35.83
-48.36
SW CRE
$W\,m^{-1}$
High cloud
%
Total cloud
%
Latitude
Latitude
Hadley
Jet

# N. Atl. DJF

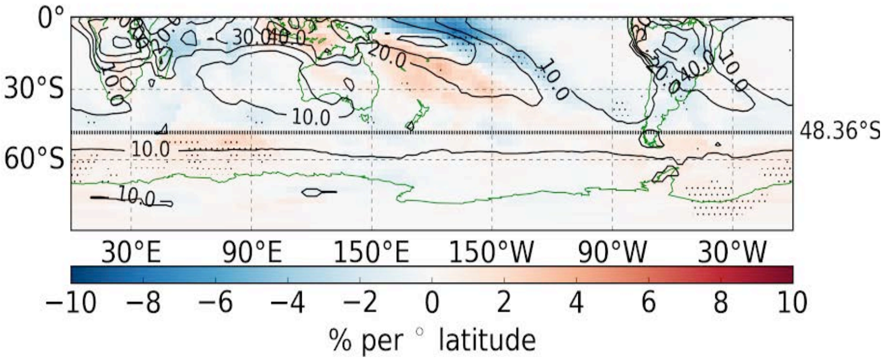

High Cloud
LW CRE
SW CRE
Hadley Cell
Storm Track
DJF
Regression of High Cloud Cover on Hadley Cell Edge Latitude
Regression of LW CRE on Hadley Cell Edge Latitude
Regression of SW CRE on Hadley Cell Edge Latitude
Regression of High Cloud Cover on Storm Track Latitude
Regression of LW CRE on Storm Track Latitude
Regression of SW CRE on Storm Track Latitude
24.45°N
55.62°N
60°N
30°N
0°
30°W
% per ° latitude
$Wm^{-2}$ per ° latitude



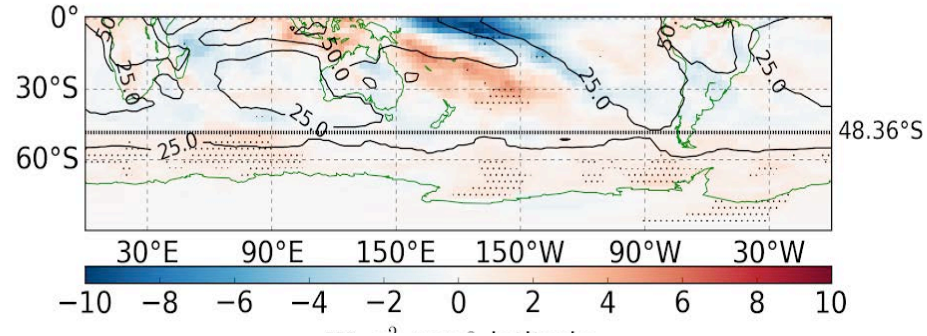
High Cloud
N. Atl.
DJF
Total Cloud
SW CRE
Hadley Cell
Storm Track
DJF
Regression of High Cloud Cover on Hadley Cell Edge Latitude
DJF
Regression of Total Cloud Cover on Local Hadley Cell Edge Latitude
DJF
Regression of SW CRE on Hadley Cell Edge Latitude
24.45°N
% per ° latitude
$Wm^{-2}$ per ° latitude
DJF
Regression of High Cloud Cover on Storm Track Latitude
DJF
Regression of Total Cloud Cover on Storm Track Latitude
DJF
Regression of SW CRE on Storm Track Latitude
55.62°N
60°N
30°N
0°
30°W

# Regressions to Eddy driven Jet
## DJF S. Oc.

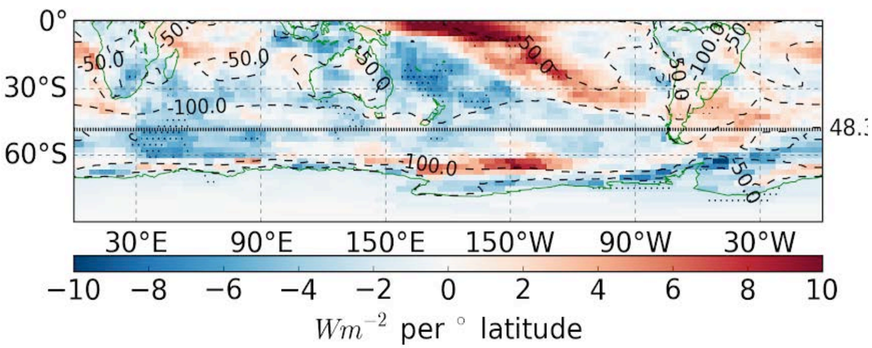
### High Cloud



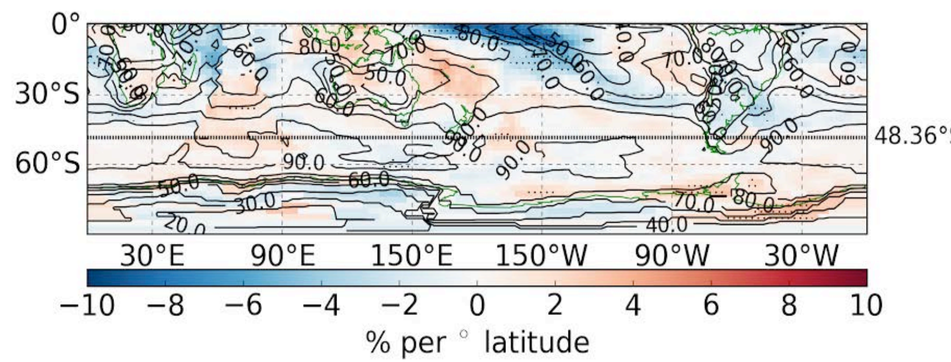

### LW CRE

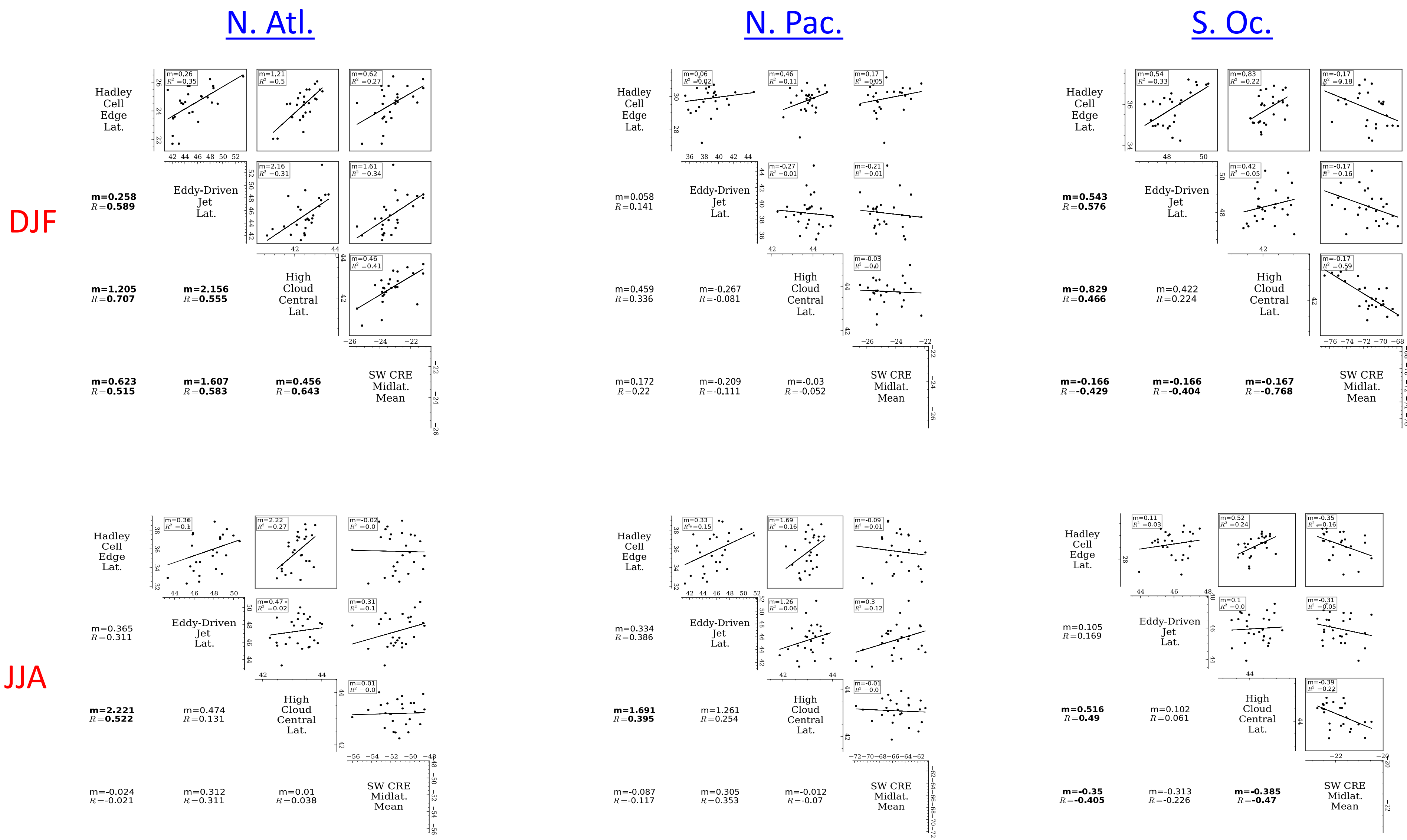



### SW CRE




### Total Cloud

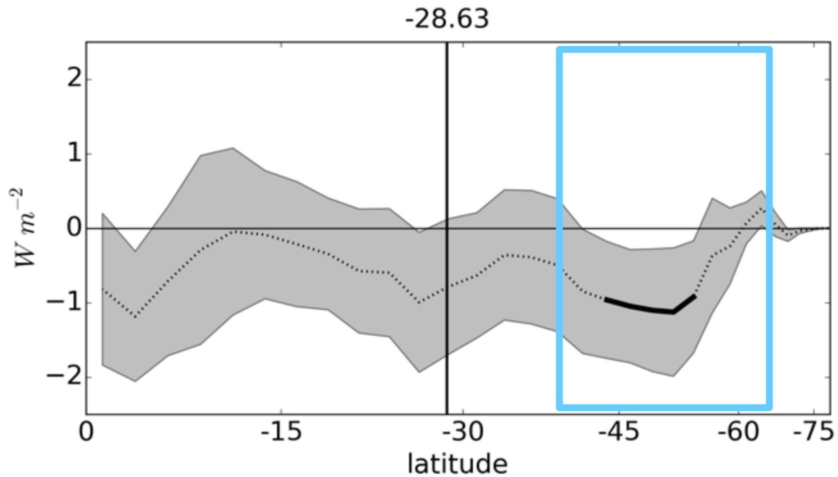




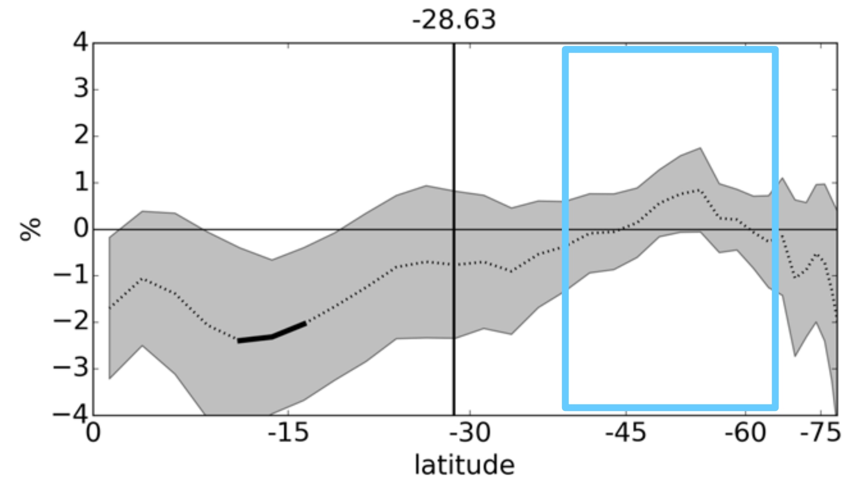

- Hadley cell shifts correlate with high cloud changes in almost all basins/seasons
- Radiative signature of poleward cloud shifts is complex and different in different basins

# Regression on Hadley cell in JJA

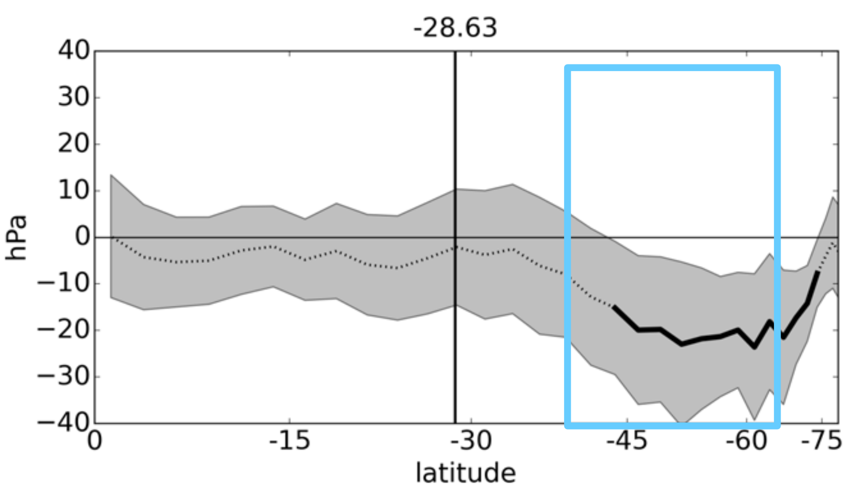
SW CRE



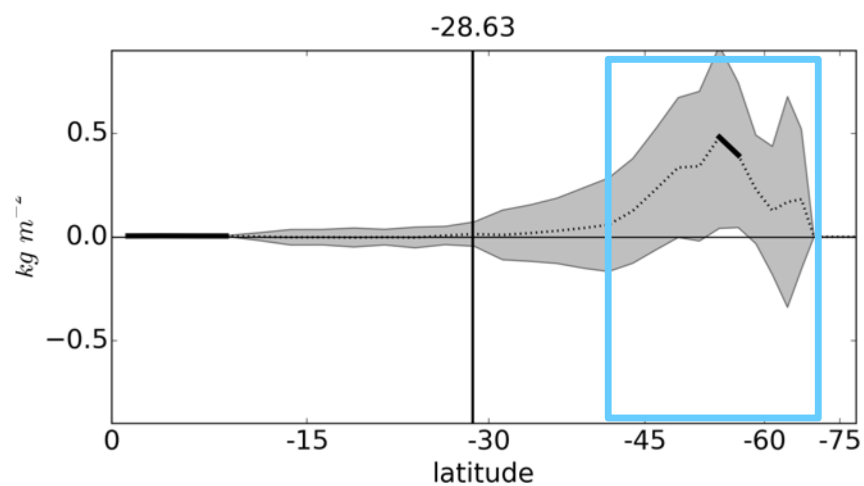

Total cloud cover

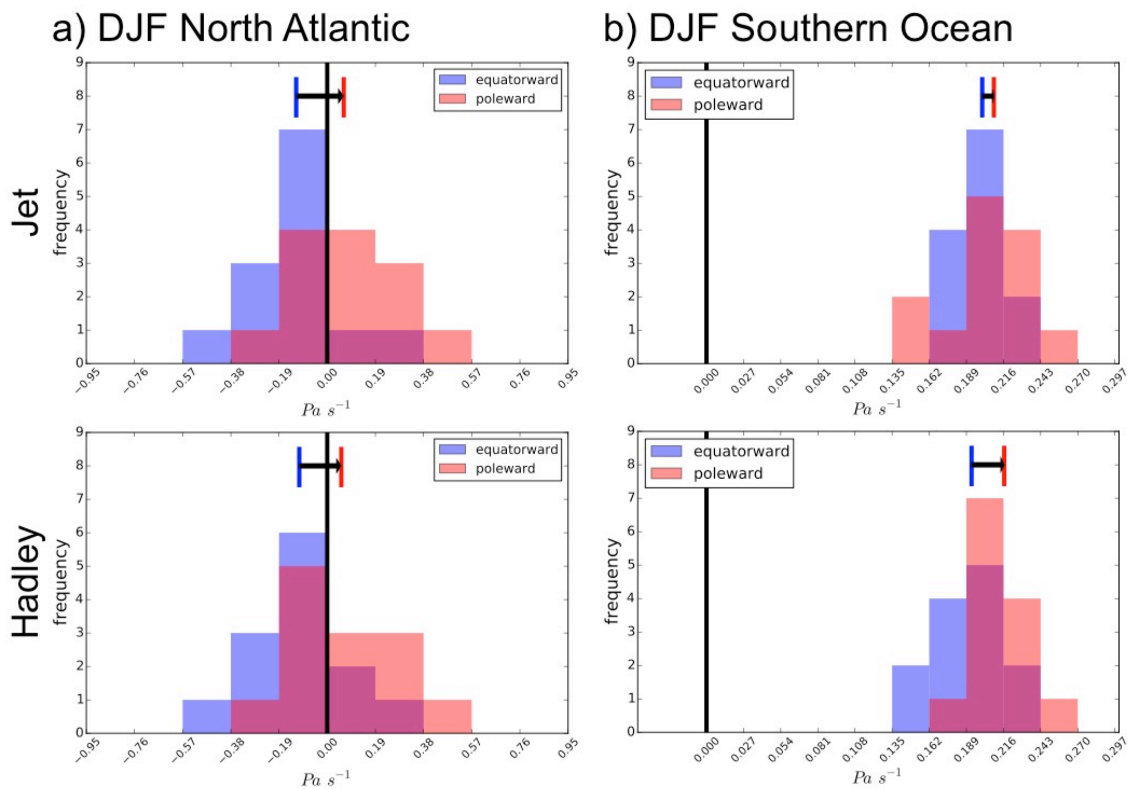



Mean cloud top pressure




Cloud water path

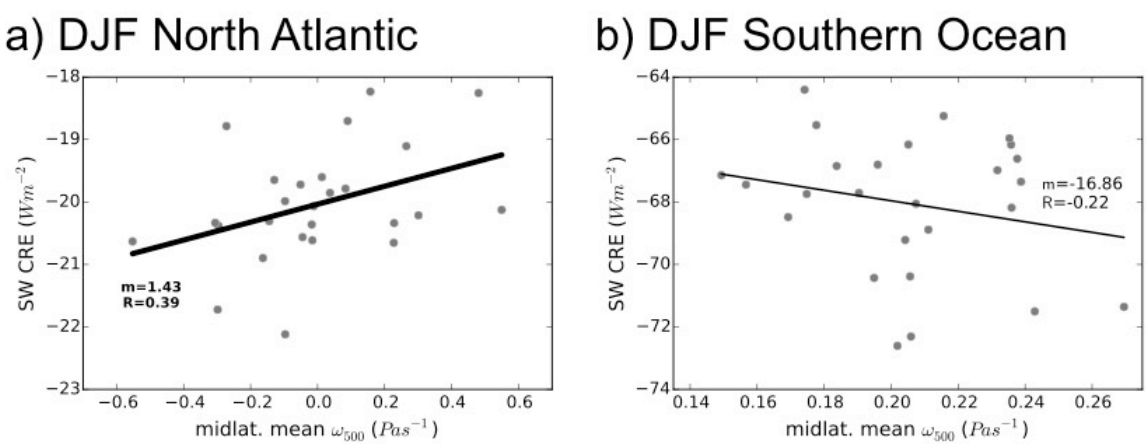




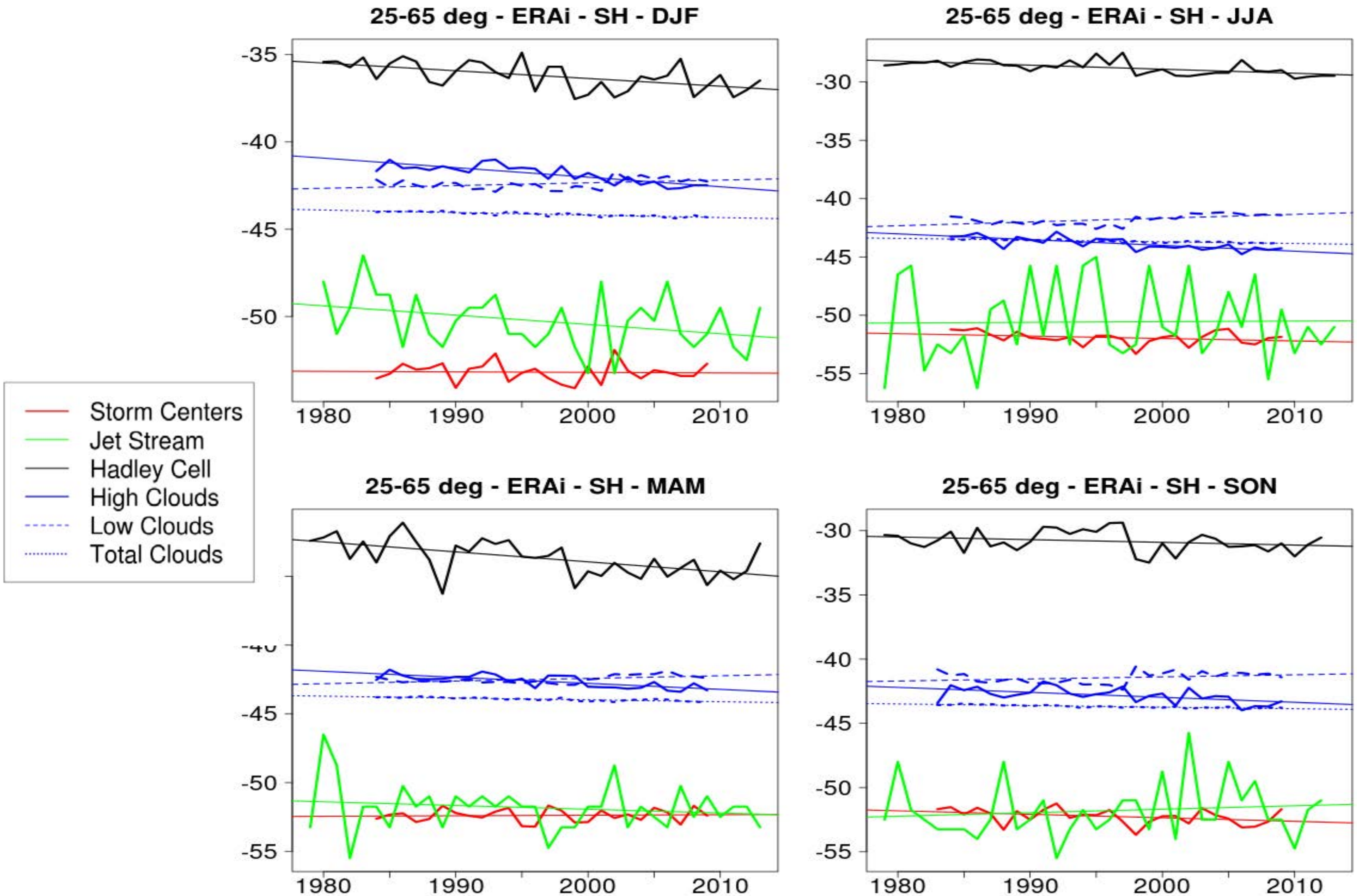

W500 changes with Hadley and jet shifts:

- N. Atlantic changes much stronger and shifting from ascend to subsidence
- S. Ocean changes smaller and shifting from weaker to stronger subsidence

- N. Atlantic ascend-to-subsidence shift causes radiative warming
- S. Ocean weaker-to-stronger subsidence shift causes radiative cooling



# Trends in cloud and dynamics central latitudes in the last 29 years




- Hadley cell and high clouds have been shifting consistently poleward at rates of 0.35-0.72 degrees/decade or about 1.5 degrees in the last 30 years

- Hadley cell expansion would be the primary culprit for the observed cloud poleward shifts